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Optimal adoption strategies for conservation tillage technology in Michigan

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OPTIMAL ADOPTION STRATEGIES FOR CONSERVATION TILLAGE TECHNOLOGY IN MICHIGAN

By

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ABSTRACT

OPTIMAL ADOPTION STRATEGIES FOR CONSERVATION TILLAGE TECHNOLOGY IN MICHIGAN

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Adoption of the no-till system of conservation tillage has been slower than many proponents expected, even though for many soils it appears to be more profitable than conventional tillage. This study evaluates whether dynamic adjustment costs due to machinery replacement and learning curves may delay no-till adoption. The effect of risk aversion on no-till adoption also is examined.

The study determines optimal adoption strategies for two representative corn and soybean producers using a dynamic programming model. One of the representative farmers maximizes expected profit. The other representative farmer is risk-averse, and maximizes an expected utility function of net income.

Crop yield parameters were estimated using crop growth simulation models. The mean estimated crop yields are slightly higher for the no-till system than for conventional tillage, but only the differences for soybean yields are statistically significant. Estimated mean revenues net of variable costs also are slightly higher for the no-till system.

Based on the estimated crop yields, the optimal adoption strategy for the profit-maximizing farmer is to immediately adopt the no-till system. If equal crop yields for the alternative tillage systems are assumed, the profit-maximizing farmer often delays adoption until currently-owned machinery has aged several years. A substantial learning curve also delays no-till adoption in this case.

Based on the estimated crop yields, the risk-averse, expected utility-maximizing farmer often delays no-till adoption until currently owned machinery has aged several years. If equal mean crop yields are assumed, the expected utility-maximizing farmer never adopts no-till unless there is little or no learning curve.

The results suggest that machinery replacement issues and learning curves affect the timing of no-till adoption by the profit-maximizing farmer and the risk-averse, expected utility-maximizing farmer. The machinery replacement issues and learning curves are particularly important to the risk-averse farmer. Both representative farmers would prefer to reduce learning costs by renting a no-till planter on a limited acreage. Technical support and opportunities to rent no-till planters appear to be critical components of no-till promotion programs.

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Chapter 1

EXPLANATION OF TECHNOLOGY ADOPTION LAGS

Introduction

Agricultural technologies that were largely developed and promoted by public research and extension institutions have provided the United States with an abundance of inexpensive food and fiber. Examples of these technologies include hybrid seed, pesticides, artificial insemination, and various innovations in farm machinery. The adoption of these productivity-increasing technologies in the U.S. has usually been very rapid. Public agricultural research and extension institutions in the U.S. now emphasize the development and promotion of agricultural technologies which minimize adverse environmental impacts. Examples include integrated pest management (IPM) systems and conservation tillage systems. But adoption of the environmentally oriented technologies has been relatively slow, causing some to doubt whether they are profitable and whether the money allocated to the development and promotion of these technologies has been well spent. Greater understanding of farmers' adoption decisions is needed in order to answer these questions and design more effective programs to promote new technology.

Agricultural technology adoption has been intensively studied by agricultural economists and rural sociologists for at least 50 years, and many factors affecting adoption rates have been examined. Rural sociologists such as Ryan and Gross (1943) and Rogers (1962) have usually examined the influence of rural communication networks and characteristics of farmers on the rate at which different farmers adopt innovations. More recent sociological work has evaluated the effect of innovation characteristics, including compatiblity, complexity, divisibility, and communicability, on rates of adoption (Fliegel and Kivlin, 1966; Rogers, 1983). Griliches established the need to analyse the profitability of new technology when explaining adoption rates in his 1957 study of hybrid corn. Subsequent empirical analyses confirmed that economic variables influence adoption rates, but usually have not identified mechanisms for this influence. Another group of economists, including O'Mara (1971, 1983) and Stoneman (1983), have proposed theoretical models for adoption lags which are based on Bayesian updating of subjective probability distributions. However, empirical support for these Bayesian learning models is scarce and subject to alternative explanations (Lindner and Gibbs, 1990). A few economic analyses (Byerlee and Polanco, 1986; Szmedra et al., 1990) have examined the optimal sequence for adopting interrelated agricultural innovations.

An important but generally neglected topic is the relationship between technology adoption decisions and investment decisions. In the highly mechanized agriculture of the U.S., investment and replacement decisions for farm machinery have critical impacts on the profitability and financial viability of farm operations. First, the costs associated with obtaining and operating agricultural machinery usually account for a major share of fixed and variable production costs. Second, the choice of agricultural machinery imposes constraints and design parameters on annual choices of technology and levels of production inputs. Third, agricultural machinery decisions can greatly increase or reduce farm-level financial and business (production) risks[1].

The risks associated with machinery investments increase greatly when the machinery embodies new technology. The performance of new technology is almost always more uncertain than that of familiar old technology. New technology often is difficult to learn how to use effectively and often must be adapted to the specific soil and other resource conditions of an individual farm. Hence, new technology is often described as exhibiting a "learning curve" (Mahd and Pindyck, 1989), an increase in productivity that occurs during the initial years of use by learning how to best adapt the technology and use it most efficiently.

When farmers consider using machinery which embodies new technology they also must consider how to acquire that technology. Purchasing new machinery exposes the farmer to potentially large financial losses. Machinery values fall dramatically in the first and second years of use. The technology may also be rendered obsolete by improved, new technology (Balcer and Lippman, 1984; Stefanou, 1987), in which case the resale value may drop to near the value of scrap metal. The machine's owner is responsible for all repair costs, whereas a short-term renter of machinery is usually responsible only for minor repairs. The combination of high or possibly very high costs and uncertain benefits discourages many farmers from purchasing machinery

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[1] Business risks are defined as the risks of operating a business that would be present with 100% equity financing. Financial risks are the additional risks that a business faces as a result of debt financing (Boehlje and Eidman, 1984).

that embodies new technology. However, purchased machinery is always available when needed to complete operations in a timely manner, which is necessary to obtain maximum crop yields. Rented machinery often may not be available during the optimal periods to perform necessary operations. Furthermore, renting machinery is generally more costly in the long run than purchasing machinery because rents include profits for the machine's owner and returns for risk-taking. Therefore, U.S. farmers usually own most of the machinery they operate[2], but ownership of machinery which embodies new technology is risky.

Conservation Tillage and No-Till Technology

Conservation-tillage systems are an example of new technology that is largely embodied in farm machinery and has been heavily promoted during the last 25 years. These systems are designed to leave more crop residue on the soil surface in order to reduce soil erosion. Conservation-tillage systems may be divided into three types: no-till systems in which no tillage is performed before planting; ridge-till systems in which only the tops of ridges are tilled before planting; and reduced-tillage systems in which a chisel or disk plow is substituted for the moldboard plow and secondary tillage operations are reduced. The no-till system often reduces soil erosion by 85% or more compared to conventional tillage (Griffith et al., 1986).

The no-till system also has been promoted because it greatly reduces labor requirements, machinery operating costs (fuel, oil,

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[2] Frequent exceptions are fertilizer applicators, pesticide sprayers, and harvesting equipment.

repairs), and machinery fixed costs compared to both conventional tillage and other conservation tillage systems. Furthermore, by conserving more soil moisture, the no-till system can provide crop yields that are equal to or greater than those for conventional tillage on many important soils in the U.S. corn belt (Mannering and Amemiya, 1987). Although the no-till system usually increases herbicide costs, most budget comparisons (e.g. Siemens and Oschwald, 1978; Klemme, 1983; Doster et al., 1983) have indicated that if crop yields for no-till are equal to or greater than those for conventional tillage, the no-till system provides higher net revenues than conventional tillage.

However, adoption of the no-till system of conservation tillage has been slow, even on soils for which agronomic trials have shown greater or equal crop yields for no-till than for other tillage systems. A 1975 study by the U.S. Dept. of Agriculture reported that 2.2 million acres, or 1.5% of U.S. cropland was planted with the no-till system in 1974 and predicted that 65% would be planted with no-till by the year 2000 (Phillips et al., 1980). However, only 5.3% of U.S. cropland was planted with no-till in 1990 (Economic Research Service, 1992). No-till adoption also has been slow in Michigan, where relatively cool temperatures in May and June slow early crop growth. The crop residues left on the surface by no-till further reduce soil temperatures and early crop growth, and most agronomic trials have not demonstrated a statistically significant increase in crop yields for the no-till system (Hesterman et al., 1988). Yet, the no-till system generally provides crop yields on well-drained, sandy soils in southern Michigan that are approximately equal to crop yields for conventional tillage.

The slow rate of adoption has frustrated Soil Conservation Service (SCS) staff and other no-till proponents, who wonder why farmers are not paying attention to budget analyses indicating that no-till is more profitable than other tillage systems. Some agricultural economists have used stochastic dominance techniques to examine whether risk aversion discourages farmers from adopting conservation tillage systems, including no-till. Klemme's (1985) analysis was based on Indiana data showing higher crop yields for conventional tillage than for conservation tillage systems. He found that if a per-acre soil loss value that approximately equalled the difference in returns to labor and management between conventional tillage and chisel plow or no-till systems were subtracted from the returns for conventional tillage, the chisel plow or no-till systems would exhibit second-degree stochastic dominance. Where net returns to management are higher for conservation tillage than for conventional tillage, Williams (1988) found that risk averse farmers would prefer the conservation tillage systems. These stochastic dominance results do not suggest that risk aversion is responsible for slow adoption of conservation tillage systems.

Budgets and stochastic dominance provide static comparisons of alternative technologies. They assume that the mean productivity of the alternative technologies does not change over time as a result of technological improvement or experience. They also ignore the possibility that the farmer may already own machinery that is well-adapted for one technology but is ill-suited for other technologies. Budgets and stochastic dominance either assume that the farmer can costlessly exchange the current machinery for whatever machinery is optimal for the alternative technologies or that no machinery is owned initially.

However, conservation tillage systems, especially no-till, must be adapted to the unique soil conditions of individual farms (Nowak, 1983). Such adaptation often requires years of trial and error (Lockwood, 1987). Nowak and Korsching (1985) documented that conservation tillage adopters find it difficult to manage large amounts of surface crop residue until they have accumulated several years of experience with those systems. Production costs tend to be higher and crop yields tend to be lower during the initial years of conservation tillage adoption than in the long-run as farmers learn what adjustments they need to make.

Epplin et al. (1982) suggested that optimal machinery replacement strategies would delay the adoption of a conservation tillage system for wheat production in Oklahoma. Cost budgets suggested that a two-till conservation tillage system had slightly lower costs than the conventional tillage sytem. However, Epplin et al. found that if the conventional tillage machinery complement was more than three years old, the profit-maximizing replacement strategy was to keep it until the end of its useful life.

Shrestha et al. (1987) and Smith and Hallam (1990) analyzed alternative tillage systems with multiperiod linear programming models in order to consider investment, replacement, and financing issues. Like Epplin et al. (1982), Smith and Hallam (1990) found that it often is more profitable to wait until conventional tillage equipment is worn out before changing to conservation tillage equipment.

Epplin et al. (1982) suggested that machinery leasing possibilities should be considered in economic analyses of alternative tillage systems. A survey of Ohio farmers (Ladewig and Garibay, 1983) also found that an inability to rent planters and drills was an important explanatory variable for not using conservation tillage.

The economic studies that have examined dynamic issues relating to conservation tillage adoption suggest that dynamic adjustment problems and machinery replacement have important effects on adoption decisions. A major limitation of these studies of dynamic issues for no-till adoption is that the effect of risk aversion on dynamic adoption decisions was not considered. Knowing what effect machinery replacement decisions, learning curves, planter rental opportunities, and risk aversion have on optimal adoption strategies for the no-till technology could help accelerate its adoption, and thereby reduce soil erosion.

Problem Statement

In a dynamic perspective, farmers' choice of technology cannot be separated from their choice of durable machinery. This is especially true when farmers are choosing between a conventional tillage system and the no-till system of conservation tillage, which requires a different planter. The choice of durable equipment alters the costs and returns for all subsequent variable input use decisions. The choice of durable equipment also exposes the farm to more risk than variable input decisions because the durables are expensive and costly to change. The purpose of this study is to evaluate optimal dynamic strategies for durable selection and acquisition, then illustrate how the riskiness of durable choices influences the adoption of new technology. Strategies for adopting the no-till system of conservation tillage in southern Michigan are examined in this illustration.

Objectives

1. Determine the optimal dynamic strategies for choosing between conventional tillage and no-till technology and acquiring the necessary machinery for two representative farmers. Both representative farmers currently grow 400 acres of corn and 200 acres of soybeans with conventional tillage in southern Michigan. One representative farmer maximizes expected profit. The other farmer is risk-averse, and maximizes an expected utility function of net profit.

2. Evaluate the effect of the age of currently owned machinery on the optimal technology selection and machinery acquisition strategies[3] of the profit-maximizing farmer and the expected utility-maximizing farmer. Assess whether current disincentives (if they exist) for profit-maximizing farmers and expected utility-maximizing farmers to adopt conservation tillage systems will be overcome in the normal course of machinery replacement.

3. Evaluate the effect of initially higher costs due to learning curves on the optimal adoption strategies of the profit-maximizing farmer and the expected utility-maximizing farmer.

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[3] Together, these will be called the optimal adoption strategies.

4. Evaluate the effects of uncertain crop yields and crop prices on the optimal adoption strategies of the profit-maximizing farmer and the expected utility-maximizing farmer.

5. Evaluate the effect of planter rental policies by the Soil Conservation Service and agricultural equipment dealers on the optimal adoption strategies of the profit-maximizing farmer and the expected utility-maximizing farmer.

Hypotheses

1. The profit-maximizing farmer and the risk-averse, expected utility-maximizing farmer will adopt the no-till system, but the timing of this adoption will depend on the age of currently-owned machinery, the magnitude of learning curves, and whether opportunities to rent no-till planters on a limited acreage exist.

2. The profit-maximizing farmer and the risk-averse, expected utility-maximizing farmer will more often adopt the no-till system (as other factors are varied) when their machinery has accumulated several years of use than when their machinery is one or two years old.

3. The profit-maximizing farmer and the risk-averse, expected utility-maximizing farmer will more often adopt the no-till system when they expect little or no learning curve effect on production costs than when they expect a large learning curve effect.

4. Even a slight level of risk aversion will make the risk-averse, expected utility-maximizing farmer adopt the no-till system less often than the profit-maximizing farmer. Furthermore, the expected utility-maximizing farmer will adopt the no-till system less often as the magnitude of risk aversion is increased.

5. Both the profit-maximizing farmer and the risk-averse, expected utility-maximizing farmer will choose to rent a no-till planter on a limited acreage if this opportunity is available. It is further hypothesized that the profit-maximizing farmer and the risk-averse, expected utility-maximizing farmer will more often rent a no-till planter on a limited acreage when learning curves have strong effects on production costs than when there are little or no learning curve effects. This hypothesis implies that the profit-maximizing and risk-averse, expected utility-maximizing farmers choose to rent a no-till planter on a limited acreage in order to reduce learning costs.

If the profit-maximizing farmer and expected-utility maximizing farmer more often adopt the no-till system when their existing machinery is old than when it is new (Hypothesis 2), the other hypotheses have an important implication for the timing of adoption. Since the ages of the existing planter and tractor increase each year, any variable that makes the two representative farmers more likely to adopt the no-till system will accelerate adoption. Similarly, any variable that makes them less likely to adopt the no-till system will delay adoption. Furthermore, if the profit-maximizing farmer and the risk-averse, expected utility-maximizing farmer are truly representative of large groups of farmers, then variables which make them more likely to adopt the no-till technology will accelerate no-till adoption by the general population of farmers.

Organization of the Dissertation

The remaining chapters are organized as follows. Chapter 2 presents the economic theory that underlies the analysis. Chapter 3 presents the analytical model for the determination of optimal adoption strategies. Chapter 4 explains how the model parameters were estimated. Chapter 5 presents results for the crop yield estimates, comparative budget analysis, and stochastic dominance analysis. Chapter 6 presents the optimal adoption strategies for the profit-maximizing and risk-averse, expected utility-maximizing farmers. These results are determined by the deterministic and stochastic dynamic programming models, respectively. Finally, Chapter 7 summarizes the earlier chapters and presents conclusions.

Chapter 2

THEORETICAL FOUNDATIONS FOR THE ANALYSIS

The neoclassical theory of the firm starts with a production function, input prices, and output prices, then proceeds to derive optimality conditions in static equilibrium for choice of output, output level, choice of inputs, and input levels. The standard objectives for the optimization are profit maximization (constrained or unconstrained) or cost minimization subject to a minimal production level. In the static theory of the firm, time is only considered as the short-run, when some inputs are held fixed, or the long-run, when all inputs are allowed to change (Beattie and Taylor, 1985; Varian, 1984). This view of short-run decisions is mathematically convenient, because it allows optimality conditions to be derived through simple constrained optimization, but has been soundly criticized for its lack of realism (Stigler, 1939; Johnson, 1956; Lucas, 1967; De Alessi, 1967; Georgescu-Roegen, 1970; Treadway, 1970; Antle, 1983). An intertemporal theory of the firm is required to analyze the demand for production durables such as agricultural machinery that provide services over time, are costly to adjust or exchange, and are often lumpy and indivisible[1].

Production durables are stocks which provide flows of services in more than one production period (i.e. a crop season). The flows of services are similar to variable inputs such as seed and fertilizer in that they are consumed within a production period. In the case of machinery, the service flows are usually variable. Thus, a crop

[1] A few texts (Hicks, 1946; Henderson and Quandt, 1980; Doll and Orazem, 1984) present both atemporal and temporal theories of the firm.

production function is a function of variable inputs and variable service flows from production durables[2]. The set of production durables is often called the "plant" of the firm. The cost of changing some of the inputs in the short run may vastly exceed the expected benefits. In this sense, some of the inputs may be regarded as being fixed in the short run (De Alessi, 1967).

Individual demand for a production durable is determined through investment analysis because expenditures and received services occur in multiple periods and must be dated and discounted to a common time period in order to be comparable. The dating and discounting are necessary because of the time value of money (Aplin et al., 1977). The investment analysis may utilize a multiperiod or continuous time present value model or it may be based on a dynamic optimization model, such as dynamic programming. These techniques are discussed below.

Both static and dynamic models of production decisions often need to consider the effect of uncertain outcomes and the decision maker's risk preferences on optimal choices. The expected utility model is used to analyze these risk effects on production decisions.

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[2] Placing durable stocks in the production function as inputs is sometimes acceptable for econometric estimation (Griliches, 1960; Day, 1967), although it may lead to biased estimates (Yotopoulos, 1967). However, this often causes major problems for analyses of production technology. First, it ignores the possibility of renting durable services. Second, it prevents substitution possibilities from being considered. For example, farmers substitute herbicide treatments for the hours of tractor and cultivator services required to obtain similar weed control. Third, it ignores the fact that most machinery durables are transformed by use such that they are able to provide less services or services at higher cost in subsequent periods. Thus, the quantity of service to demand from a production durable in each period may be a choice variable, but cannot be considered when the production function contains durable stocks rather than durable service flows.

Risk Analysis Using the Expected Utility Model

The expected utility model for ordering action choices that have uncertain outcomes[3] provides a useful framework to model the selection of optimal dynamic strategies for risk-averse farmers. The expected utility model is based on a set of axioms regarding human behavior in choosing among risky alternatives. The most essential of these axioms are (Robison and Barry, 1987):

(1) Ordering of Choices. For any two choices A_1 and A_2, the decision maker either prefers A_1 to A_2, prefers A_2 to A_1 or is indifferent.

(2) Transitivity of Choices. If A_1 is preferred to A_2, and A_2 is preferred to A_3, then A_1 must be preferred to A_3.

(3) Substitution or Independence among Choices. If A_1 is preferred to A_2, and A_3 is some other choice, then the risky choice $p \bullet A_1 + (1-p) \bullet A_3$ is preferred to the risky choice $p \bullet A_2 + (1-p) \bullet A_3$, where p is the probability that A_1 or A_2 occurs.

(4) Certainty Equivalence among Choices. If A_1 is preferred to A_2, and A_2 is preferred to A_3, then some probability p exists that the decision maker is indifferent to having A_2 for certain or receiving A_1 with probability p and A_3 with probability (1-p). A_2 is called the certainty equivalent of $p \bullet A_1 + (1-p) \bullet A_3$.

If these axioms are satisfied, then a utility function can be formed which represents the decision maker's preferences regarding the risky

[3] This is only a bare outline of expected utility theory. See Robison et al. (1984) or Robison and Barry (1987) for excellent, more comprehensive presentations.

action choices. The optimal choice then is the one which maximizes the expected value of this utility function. It is assumed that the decision maker has subjective estimates of the probability of occurrence for every possible outcome. These subjective probability estimates are the weights used to calculate the value of the expected utility function.

Estimating an individual's utility function for risky action choices is extremely difficult (Robison et al., 1984; Alderfer, 1990). One way to rank preferences over risky action choices that avoids trying to estimate utility functions is to use stochastic dominance or other risk efficiency criteria (King and Robison, 1984). The easiest of the risk efficiency criteria to use is first-degree stochastic dominance (Hadar and Russell (1969). Suppose the y outcomes for two risky action choices are described by the cumulative distribution functions F(y) and G(y). The risky action choice defined by F(y) is said to exhibit first degree stochastic dominance over the risky action choice defined by G(y) if $F(y) \leq G(y)$ for all possible values of y and the inequality is strict for at least one value of y. First-degree stochastic dominance implies that all decision makers for whom y has a positive marginal value will prefer the action choice defined by F(y) to the action choice defined by G(y). First-degree stochastic dominance thus imposes a very weak restriction on preferences. The primary difficulty with first-degree stochastic dominance is that it cannot rank many risky action choices.

Second-degree stochastic dominance (Hadar and Russell, 1969) is a more useful risk efficiency criterion because it is able to rank more risky action choices than does first-degree stochastic dominance. The risky choice defined by cumulative distribution function (CDF) F(y) is said to exhibit second-degree stochastic dominance over the risky choice defined by CDF G(y) if:

$$\int_{-\infty}^{x} F(y)\,dy \le \int_{-\infty}^{x} G(y)\,dy,$$

for all values of x and the inequality is strict for at least one value of x. Second-degree stochastic dominance implies that all risk-averse decision makers who derive a positive marginal utility from y will prefer the risky choice defined by F(y) to the risky choice defined by G(y). Again, second-degree stochastic dominance imposes a rather weak assumption on decision maker preferences, but is unable to rank many risky action choices. More risky choices can be ranked if bounds can be imposed on the decision-maker's risk preferences by using the method of stochastic dominance with respect to a function (Meyer, 1977). However, even stochastic dominance with respect to a function cannot order all risky choices. Furthermore, all stochastic dominance comparisons are only valid for multiperiod analyses under very restrictive assumptions.

The other method often used to rank preferences over risky action choices is to use a parametric approximation of the expected utility function (Lambert and McCarl, 1985). This entails: (1) choosing a functional form from a set of possible utility functions that are both mathematically tractable and somewhat consistent with empirical evidence; (2) determining an appropriate risk-aversion parameter for the utility function; (3) determining objective or subjective probabilities for the possible outcomes of each risky action choice; and (4) calculating the expected value of this function for each risky action choice. Properties of several popular functional forms are summarized by Lins et al. (1981) and Selley. This approach is always able to rank risky action choices, but the ranking is conditional on very restrictive assumptions about risk preferences that often have little empirical foundation.

Most empirical research regarding risk preferences has attempted to estimate levels of risk-aversion for various groups of decision makers. One can determine whether an individual is risk-averse, risk-neutral (indifferent to risk), or risk-loving by examining whether the second derivative of the individual's utility function is negative, zero, or positive, respectively. However, since the utility function is only unique up to a positive linear transformation, Arrow (1974) and Pratt (1964) independently suggested dividing the second derivative of the utility function by the first derivative in order to measure the magnitude of risk aversion. Two widely-used measures of risk aversion are therefore the absolute risk aversion coefficient:

$$R_{ara} = -U''(y)/U'(y),$$

and the relative risk aversion coefficient:

$$R_{rra} = -y \bullet U''(y)/U'(y),$$

which are measured at a specified monetary outcome, y. Because these risk aversion coefficients are functions of the monetary outcome levels, it is difficult to compare risk-aversion estimates from one empirical study based on one set of monetary outcomes with risk aversion estimates based on a different set of monetary outcomes.

If decision makers are assumed to have constant relative risk aversion (CRRA), or constant partial relative risk aversion (CPRRA), then the relative risk aversion coefficient measured at one monetary outcome level can be applied to a wide range of outcome levels. CRRA implies that relative risk aversion stays constant as wealth changes (Pratt, 1964). CPRRA implies that relative risk aversion stays constant as income changes (Menezes and Hanson, 1970). The assumption of CRRA or CPRRA is consistent with empirical observations that absolute risk-aversion measures generally decline as income and wealth increase (Alderfer, 1990; Chavas and Holt, 1990; Pope and Just, 1991). However, the Chavas and Holt (1990) study suggests that relative risk aversion may not be constant either.

Input Demands under Uncertainty in a Static Model

Risk-averse, expected utility-maximizing farmers generally make different production decisions than expected profit-maximizing farmers. Some clear results have been obtained regarding the effects of price uncertainty on production decisions by expected utility-maximizing farmers. Sandmo (1971) shows that an increase in the spread of price outcomes around a constant mean price reduces input demand by risk-averse, expected utility maximizers. Sandmo (1971) also shows that if the decision maker's risk preferences exhibit decreasing absolute risk aversion (DARA) and prices are uncertain, an increase in fixed costs reduces variable input demand. However, when analyzing technology adoption decisions it is appropriate to examine the effects of uncertainty in the production function, which are not as clear as the price uncertainty effects. All crop production is uncertain due to unpredictable weather and agricultural pests, but when unfamiliar new technology is being considered, the production function becomes especially uncertain.

Pope and Kramer (1979) show that the effect of production function uncertainty depends on: (1) whether the stochastic component of the production function has a multiplicative or additive effect on output; and (2) whether the input is risk-increasing or risk-reducing. Examples of risk-reducing inputs are many herbicides and insecticides, if applied correctly[4]. Consider an expected-utility maximizing farmer who is risk averse ($U'(\pi) > 0$, $U''(\pi) < 0$, where $U(\pi)$ is the utility of profit and $U'(\pi)$ and $U''(\pi)$ are first and second derivatives). The production function is:

$q = F(X,\epsilon)$, where X is a vector of input levels x_j, $j = 1 \ldots M$, and ϵ is a random disturbance.

The first order conditions for profit maximization can be written as:

$$E[U'(\pi)\bullet(P\bullet F_j(X,\epsilon) - c_j)] = 0, \ j = 1 \ldots M, \text{ or}$$

$$P\bullet E[F_j(X,\epsilon)] - c_j = -P\bullet Cov[U'(\pi),F_j(X,\epsilon)] \ / \ (E[U'(\pi)]), \qquad (1)$$

where P is the output price, F_j is the marginal product of the j^{th} input, and c_j is the price of the j^{th} input. First order conditions for profit maximization are assumed to be sufficient. An input is said to be risk increasing if under risk aversion the expected value of the marginal product is greater than the factor price at the optimum. Using this definition and equation (1), x_j is marginally risk increasing if

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[4] Herbicides and insecticides are not always risk-reducing. Excessive applications of some herbicides may harm crops, particularly crops which follow the treated crop in a rotation. Careless herbicide application may harm crops in adjacent fields. Insecticide applications often kill natural predators of insect pests, and may lead to an eventual increase in the population of the target pest or secondary pests.

$Cov[U'(\pi), F_j(X,\epsilon)] < 0$. If the production function is written in its multiplicative form:

$$q = f(X) \bullet g(\epsilon);\ f_j > 0,\ f_{jj} < 0 \text{ at the optimum,} \quad (2)$$

$Cov[U'(\pi), F_j(X,\epsilon)] = f_j \bullet Cov[U'(\pi), g(\epsilon)]$. As $g'(\epsilon) > 0$, $Cov[U'(\pi), g(\epsilon)] < 0$. Therefore, the multiplicative form of the production function (2) implies that all inputs are marginally risk increasing (Pope and Kramer, 1979).

Also, given (2), the variance of q, V(q), is given by:

$$V(q) = f^2(X) \bullet V(g(\epsilon)),$$

and the marginal change in variance is given by:

$$dV(q)/dx_j = 2 \bullet f(X) \bullet f_j(X) \bullet V(g(\epsilon)) > 0.$$

Now if the production function is written in an additive form:

$$q = f(X) + h(X) \bullet \epsilon;\ f_j > 0,\ f_{jj} < 0,\ E(\epsilon) = 0,$$

and h(X) is assumed to be positive. For this function, $Cov[U'(\pi), F_j(X,\epsilon)] = h_j \bullet Cov[U'(\pi), \epsilon]$. The covariance term is negative for a risk averter and $E(P \bullet f_j) > c_j$ if and only if $h_j > 0$. Therefore, an input is marginally risk increasing only if h_j is positive. Also, for this production function,

$$V(q) = h^2(X) \bullet V(\epsilon), \text{ and}$$

$$dV(q)/dx_j) = 2 \bullet h(x) \bullet h_j(X) \bullet V(\epsilon) > 0 \text{ if and only if } h_j > 0.$$

An input only increases variance if h_j is positive.

All other things equal, a risk averter uses less of a risk increasing input than a person who is risk neutral (Pope and Kramer, 1979). Whether an input is risk increasing or risk reducing has been shown to depend on the functional form of the production function. In summary, the effect of uncertainty in the production function on input demands depends on how the uncertainty enters the production function.

Dynamic Issues for Production Durables

In addition to providing input services in more than one production period, an essential difference between production durables and variable inputs is that durables usually are costly to change. Costly changes include increasing the durable stock through investment, decreasing the durable stock through disinvestment, modifying the durable, and exchanging the durable for another. In the economic investment literature, the costs of such changes are called adjustment costs (Lucas, 1967; Gould, 1968; Treadway, 1970). Many agricultural economists have been primarily concerned with the cost of disinvestment and Johnson (1956) developed a theory of asset fixity to explain its effects. Asset fixity results when not owning a durable would increase profits but the resale value of the durable is less than its use value. Hsu and Chang (1990) recently showed that asset fixity is a special case of adjustment cost effects on investment and disinvestment.

Adjustment cost theory was developed by macroeconomists primarily in order to justify using distributed lags in econometric studies of investment behavior (Rothschild, 1971). Lucas (1967) also used adjustment costs to reconcile "U-shaped" long-run average cost curves with empirical evidence that rates of firm growth are independent of firm size (except for very small firms). Investment theorists proposed that two types of adjustment costs exist: (1) external costs due to rising short-run supply curves in the industry that supplies durable investment goods; and (2) internal costs due to reorganizing production lines, training new workers, etc. (Eisner and Strotz, 1968)[5]. Lucas (1967) also proposed that new technology is a key stimulus for investment but the new technology often is not fully effective until after a learning period, and the costs of this learning are an example of internal adjustment costs.

The investment economists generally assume a symmetric, continuous, and convex cost function for investment and disinvestment (for $I>0$: $C(I)>0$, $C'(I)>0$, $C''(I)>0$, and $C(0)=0$, where $C(I)$ is investment cost and I is gross investment). This functional form implies that investment always responds to changes in prices or costs, but the rate of response may be slow. The quadratic form of the investment cost function is mathematically convenient and the most often used (Gould, 1968). However, Rothschild (1971) argues that non-convex adjustment cost functions are just as likely and often cause no response to small changes in prices or costs. Likewise, Hsu and Chang (1990) argue that adjustment costs in agriculture probably are not symmetric. Also, when the cost of investment is not smooth, but kinked at $I=0$, Johnson's asset fixity trap results (Hsu and Chang, 1990).

One way to avoid adjustment costs is to design production durables to be flexible. Several types of durable flexibility can be distinguished, including: flexibility in efficiency (cost flexibility), flexibility in output level, flexibility in types of output, and flexibility in the types and levels of inputs with which the durable is

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[5] Lichtenberg (1988) estimates that average internal adjustment costs to expansion and replacement investment in U.S. industries equal 35% and 21%, respectively, of the investment amounts.

combined in production. A general economic definition of flexibility is that "one position is more flexible than another if it leaves available a larger set of future positions at any given level of cost" (Jones and Ostroy, 1984)[6].

Stigler (1939) and Lev (1984) define durable flexibility as having relatively constant average costs of operation across a wide range of output levels rather than having lower average costs at an optimal output level but sharply increasing average costs at higher or lower output levels. This flexibility can be called flexibility in efficiency or cost efficiency (as Heady, 1950, referred to it).

Robison and Barry (1987) suggest another type of flexibility which is defined according to whether the capacity of the durable to provide services changes with time and use. Durables are called inflexible in output when their capacity to provide services is fixed and declines with time, not use. One can extract more total services over the lifetime of such durables by using more of this capacity. An example is a barn. Durables are called completely flexible in output when they provide the same total amount of services over their lifetime, independently of the service extraction rate. The capacity of these durables declines only with use, not with time. Extreme examples are stored gasoline and fertilizer. Agricultural machinery, if kept clean, lubricated, and protected from the weather, comes close to being completely flexible in output, because its capacity declines mostly with use and relatively few parts deteriorate with age.

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[6] Marschak and Nelson (1962) propose a similar definition (their Measure III) that is both more general but less intuitive. Lev (1984) discusses the deficiencies of both general definitions.

Heady (1950) defines flexibility in terms of the costs of producing alternative outputs with the same durable. This type of flexibility is referred to here as flexibility in type of output, and is easily illustrated with product transformation (production possibility) curves (Figures 2.1 and 2.2)[7]. The product transformation curve maps the maximum amounts of one product that can be produced for given levels of production for another product and a given input set. In Figure 2.1, the long-run product transformation function between products X and Y is represented by the curve (MN). In the same figure, the short-run product transformation function is represented by the more concave curve (mn). If the firm initially produces Y_2 units of Y and X_1 units of X, but wants to reduce production of Y to Y_1 and shift resources to production of X, in the long run the firm can produce (X_3, Y_1) along curve (MN). However, some of the production durables may be designed more for the production of Y than for the production of X and in the short run it may be costly to change those durables. Thus, the short-run product transformation curve (mn) indicates that only (X_2, Y_1) can be produced until the specialized production durables are changed.

A durable that is relatively flexible in types of output can be represented by a relatively flat short-run product transformation curve (mn in Figure 2.2). A relatively inflexible durable is represented by the product transformation curve (m'n') in Figure 2.2. The inflexible durable is commonly able to produce more within a narrow range of (X, Y) combinations (the arc AB in Figure 2.2) than the flexible durable, but the flexible durable produces more if a more uneven combination of

[7] These are equivalent to Figures 2 and 5 in Heady (1950).

Figure 2.1 Short-Run and Long-Run Flexibility in Type of Output

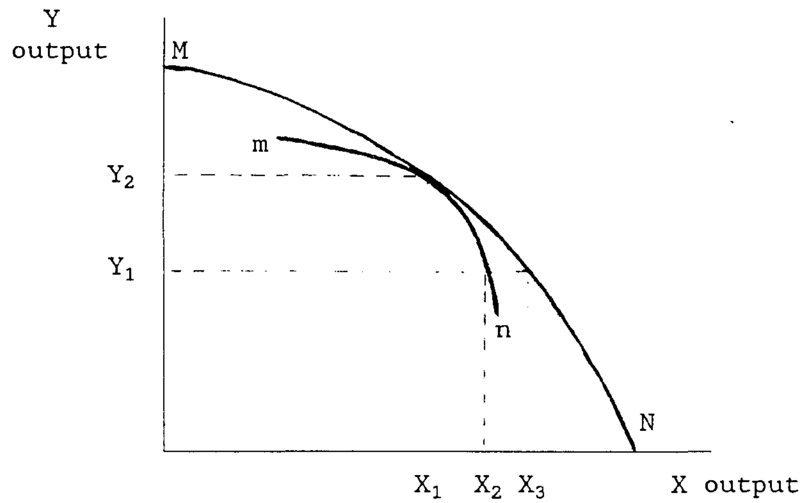
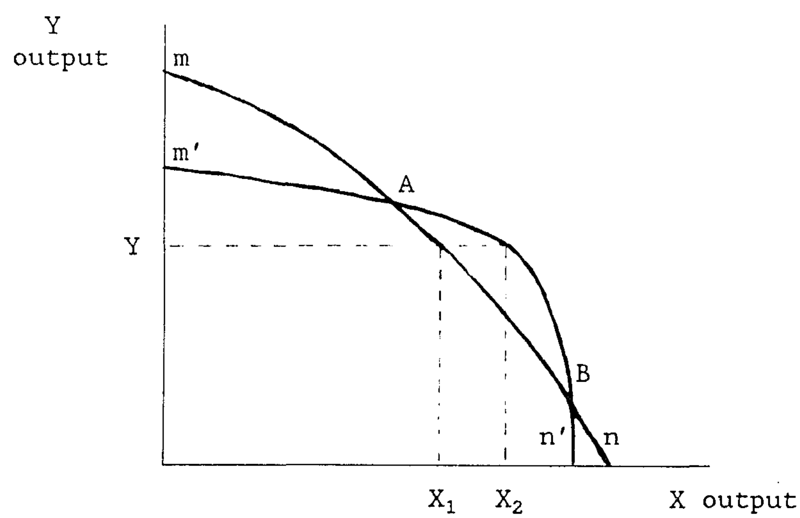


Figure 2.2 Relative Short-Run Flexibility in Type of Output



products is desired (arcs mA and Bn) in Figure 2.2). If a durable is completely inflexible in the production of two or more products, they would be called "joint products" (Debertin, 1986, Doll and Orazem, 1984).

Stigler (1939) discusses the "adaptability" of durables to changing quantities of variable inputs. This could be called flexibility in the production function. For example, farm machinery is usually designed to be operated by just one person. Putting another laborer on a tractor or combine does not increase the amount of productive services that can be extracted from the tractor or combine. Stigler also notes that having one kind of flexibility in a durable makes other kinds of flexibility less valuable.

In a dynamic perspective, flexibility is valuable because it allows the firm to respond to new information. When there is complete flexibility, a firm can ignore the possibility that prices and technology may change tomorrow and base investment decisions purely on today's prices and technology because adjustment to future prices and technology is costless. Less durable flexibility results in greater uncertainty regarding future net returns, hence more need for risk analysis. Costly adjustment but some flexibility to respond to price and technology changes increases the need for dynamic analysis.

A firm can obtain the most flexibility by postponing investments in durable assets while learning more about which investment will provide the greatest discounted future returns. This is especially true if the durable investment can only be reversed at a large economic loss, in which case the investment is said to be economically irreversible

(McDonald and Siegel, 1986; Jones and Ostroy, 1984; Pindyck, 1988). Some investments, especially those involving natural resources may effectively be permanently irreversible (Arrow and Fisher, 1974). However, most investments are reversible after a period of time. A machinery investment is reversible once the net present value of investing in a replacement machine (including whatever salvage value can be obtained for the old machine) exceeds the opportunity cost of the value of lost production from the old machine (Baldwin and Meyer, 1979).

When investment is irreversible and future demand or cost conditions are uncertain, an investment expenditure kills the option to invest those resources in the future. The possibility of waiting for new information that might affect the desirability or timing of the expenditure is forfeited (Pindyck, 1988).

> "This lost option value must be included as part of the cost of the investment. As a result, the Net Present Value (NPV) rule 'Invest when the value of a unit of capital is at least as large as the purchase and installation cost of the unit' is not valid. Instead the value of the unit must exceed the purchase and installation cost, by an amount equal to the value of keeping the firm's option to invest these resources elswhere alive -- an opportunity cost of investing" (Pindyck, 1988, p. 969).

Calculations by McDonald and Siegel (1986) show that even for moderate levels of uncertainty, in many cases the value of this opportunity cost can be so large that projects should be undertaken only when their present value is at least double the purchase and installation cost.

Several analytical results have been obtained for the value of waiting to make irreversible investments when returns are uncertain. The value of waiting to invest increases with uncertainty about future returns and decreases with the discount rate for future returns (Jones and Ostroy, 1984; McDonald and Siegel, 1986). The value of waiting to invest also increases with the length of time an irreversible investment will continue to be productive and the slower the depreciation rate (Baldwin and Meyer, 1979; McDonald and Siegel, 1986). For example, the value of waiting to invest is much greater for buildings that will last at least 30 years than for machine tools that will last only 1-2 years. The value of waiting to invest does not depend on risk aversion (Jones and Ostroy, 1984; Baldwin and Meyer, 1979; Cukierman, 1980; Bernanke, 1983).

The value of waiting to invest also counteracts one of the important results of dynamic analyses of learning by doing; namely that firms using new technology should initially produce at levels at which marginal cost exceeds marginal revenue (Rosen, 1972; Brueckner and Raymon, 1983). The rationale for producing more than the optimal level determined by static analysis is that learning increases with the level of production, so current production provides an additional, shadow value of reducing future costs. However, these analyses ignore that the extra production is an irreversible investment in reduced future costs. Majd and Pindyck (1989) show that uncertainty regarding future prices reduces the shadow value of cumulative output and increases the option value of waiting for additional information about prices before producing with the new technology. The net result of the opposing learning by doing effect and option value effect on the optimal level of production is ambiguous, depending on the relative levels of future cost reductions and future price uncertainty.

Another kind of uncertainty which may delay investment in a production durable is the possibility that a new technology may soon be introduced which makes the current technology obsolete. Rosenberg (1972) describes how the introduction of several important industrial technologies was followed by a long period during which important improvements to the technology were introduced. The value of waiting for possible new technology is another kind of option value. Balcer and Lippman (1984) analyze a model in which technology improves exogenously over time, but the timing and impact of future improvements on profits are uncertain. When a new technology is introduced, the firm decides whether to incur a fixed charge and adopt the technology immediately or defer adoption until either: (1) the technology is further improved, or (2) it appears unlikely that a new technology will be discovered soon. They find that adoption decisions depend on how the elapsed time since the last technological improvement and the pace of new discoveries affect expectations regarding future discoveries. Increased uncertainty about when new technology will appear may either speed or retard adoption, depending on what form of expectations are assumed. Not surprisingly, increases in the fixed charge for adopting a technology delay adoption.

Another dynamic aspect of nearly all durable equipment is that it eventually deteriorates or fails to work and must be replaced. Replacement problems fall into two categories: (1) replacement of equipment that deteriorates, becomes obsolete, or otherwise becomes less efficient than newer equipment; and (2) replacement of equipment that does not deteriorate but is subject to stochastic failure. Light bulbs are the standard example of equipment subject to failure, although it should be noted that much of the research on optimal replacement policies for equipment subject to failure has concerned equipment as vital as airplane parts, electric power plants, and military weapons systems. However, most agricultural machinery falls into the category of equipment that deteriorates, so the discussion here focusses on this category of replacement problems.

For equipment that deteriorates, the problem is to decide when costs due to lost efficiency or high maintenance requirements on old equipment outweigh the costs of obtaining and installing new equipment (Churchman et al., 1957)[8]. In comparing alternative replacement policies the correct measure of efficiency is the discounted value of all future costs associated with each policy. In principle, all cash costs that depend on the choice or age of the equipment must be considered[9]. Normally, the total costs of operating, repairing, and maintaining equipment (plus possible opportunity costs from lost production) increase monotonically with age. Assuming that total costs do increase monotonically with age makes it possible to ignore second-order conditions when determining optimal replacement policies.

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[8] The following three pages also draw heavily from Churchman et al. (1957).

[9] Accrued costs are only considered when they affect cash flows, as in depreciation deductions on income taxes.

The derivation of the optimal rule for replacement with identical equipment, assuming an infinite planning horizon and discrete time, follows. According to Preinreich (1940), the optimal replacement rule in continuous time was first published by Harold Hotelling in 1925, and can be found in Preinreich (1940) or Perrin (1972). However, tillage and planting machinery is generally used at discrete intervals, so the discrete time formulation is more useful here.

Consider a series of annual costs C_1, C_2, C_3, ... Assume that each cost is paid at the beginning of the year, that the initial cost of new equipment is A, and that the annual discount rate is r per period. The discounted value K_n of all future costs associated with a policy of replacing equipment after each n periods is given by:

$$K_n = \left(A + C_1 + \frac{C_2}{1+r} + \frac{C_3}{(1+r)^2} + \ldots + \frac{C_n}{(1+r)^{n-1}} \right) + \left(A + \frac{C_1}{(1+r)^n} + \frac{C_2}{(1+r)^{n+1}} + \ldots + \frac{C_n}{(1+r)^{2n-1}} \right) + \ldots \qquad (3)$$

The right hand side of this equation may be written as a geometric series and expressed in the following form:

$$K_n = \frac{A + \sum_{i=1}^{n} [C_i \,/\, (1+r)^{i-1}]}{1 - [1/(1+r)]^n}. \qquad (4)$$

If K_n is less than K_{n+1}, it is preferable to replace the equipment every n years rather than every n+1 years. Furthermore, if the best policy is to replace equipment every n years, then the two inequalities:

$$K_{n+1} - K_n > 0 \quad \text{and } K_{n-1} - K_n > 0$$

must hold. It is shown in Appendix A that $K_{n-1} - K_n > 0$ is equivalent to

$$\frac{Cn}{1 - [1/(1+r)]} < K_{n-1} \tag{5}$$

and that $K_{n+1} - K_n > 0$ is equivalent to

$$\frac{Cn_{+1}}{1 - [1/(1+r)]} > K_n. \tag{6}$$

Writing $[1/(1+r)]$ as W, inequality (5) implies that $C_n < (1-W)K_{n-1}$. By substituting n-1 for n in equation (4) and substituting this into inequality (5), one obtains

$$C_n < (1-W)\frac{(A + C_1 + C_2W + \ldots + C_{n-1}W^{n-2})}{1 - W^{n-1}}, \tag{7a}$$

or

$$C_n < \frac{(A + C_1) + C_2W + \ldots + C_{n-1}W^{n-2}}{1 + W + W^2 + \ldots + W^{n-2}}. \tag{7b}$$

The expression on the right hand side of inequality (7b) is the weighted average of all costs up to and including year n-1. The weights 1, W, W^2, ..., W^{n-2} are the discount factors applied to the costs in each period. Similarly, inequality (6) may be expressed as

$$C_{n+1} > (1-W)\frac{(A + C_1 + C_2W + \ldots + C_{n-1}W^{n-2})}{1 - W^n}, \tag{8a}$$

or

$$C_{n+1} > \frac{(A + C_1) + C_2W + \ldots + C_{n-1}W^{n-2}}{1 + W + W^2 + \ldots + W^{n-1}}. \tag{8b}$$

As a result of inequalities (7b) and (8b), the cost-minimizing replacement rules are:

(1) Do not replace if the next period's cost is less than the weighted average of previous costs.

(2) Replace if the next period's cost is greater than the weighted average of previous costs.

Numerical examples are provided in Churchman et al. (1957, p. 488) and Perrin (1972, p. 66).

Dynamic Programming

The replacement rule just derived works fine when costs in future periods can be predicted and replacement equipment is identical to the old equipment, but technology generally is not static and future costs are uncertain. For more complex and stochastic replacement problems it is advantageous to use the recursive method of dynamic programming to derive optimal replacement strategies. In fact, equipment replacement strategies were one of the first applications of dynamic programming[10].

Dynamic programming is a mathematical optimization technique that is particularly useful for sequences of interrelated decisions. The essential characteristics of a dynamic programming problem are (Hillier and Lieberman):

(1) The problem can be divided into stages, with a policy decision required at each stage.

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[10] Churchman et al. (1957) cite a study by Richard Bellman in 1955 for the RAND Corporation, entitled "Notes in the Theory of Dynamic Programming--III: Equipment Replacement Policy". This was two years before Bellman published his "Dynamic Programming" (1957) textbook.

(2) Each stage has a number of states associated with it. The states are the various possible conditions that may be in effect at each stage.

(3) The effect of the policy decision at each stage is to transform the current state into a state at the next stage.

(4) Given the current state, an optimal policy for the remaining stages is independent of the policy adopted in previous stages. Knowlege of the current state conveys all the information that is necessary for determining the current optimal policy. This is called Bellman's principle of optimality.

(5) There is a recursive relationship between the value of an objective function at stage n and the optimal value of that objective function at stage n+1 that allows the optimal value of the objective function for the entire problem to be obtained by working backward from the final stage and determining the optimal policy and associated value of the objective function at each stage.

Since sequential stages can easily represent sequential time periods and investment or replacement decisions in one period do affect opportunities in subsequent periods, dynamic programming is an appropriate technique for finding optimal investment and replacement policies for production durables.

The standard, intertemporal dynamic programming problem is formulated as follows[11]. Let x_t be an (n x 1) vector of state

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[11] The notation follows Sargent (1987).

variables at time t and let u_t be a (k x 1) vector of control variables at time t. In each period (stage) one seeks to maximize (or minimize) a one-period return function, $r_t(x_t,u_t)$. At the end of the planning horizon, denoted by T, the value function for period T+1, $W_0(x_{T+1})$ is a function only of the state variable. "Transition equations" or "laws of motion", $x_{t+1} = g_t(x_t,u_t)$, govern the effect of current state and control variables on the state variables in the next period. The complete problem is then to maximize (minimize):

$$r_0(x_0,u_0) + r_1(x_1,u_1) + \ldots + r_T(x_T,u_T) + W_0(x_{T+1}),$$

subject to having either the vector of initial state variables, x_0, or the vector of state variables at period T+1, x_{T+1}, given and subject to the transition equations:

$$_{xt+1} = g_t(x_t,u_t), \quad t = 0,\ldots,T.$$

The first step in the solution is to find the vector of control variables at the end of the planning horizon, u_T, that maximizes:

$$W_1(x_T) = \max\{r_T(x_T,u_T) + W_0(x_{T+1})\},$$

subject to $x_{T+1} = g_T(x_T,u_T)$ with x_T given. The value function $W_1(x_T)$ is then used to find the u_{T-1} that maximizes:

$$W_2(x_{T-1}) = \max\{r_{T-1}(x_{T-1},u_{T-1}) + W_1(x_T)\},$$

subject to $x_T = g_{T-1}(x_{T-1},u_{T-1})$ with x_{T-1} given, and this process is repeated until all of the u_t have been found. The state and optimal control variables in each period constitute the optimal policies. The general functional equation:

$$W_{j+1}(x_{T-j}) = \max\{r_{T-j}(x_{T-j},u_{T-j}) + W_j(x_{T-j+1})\},$$

subject to $x_{T-j+1} = g_{T-j}(x_{T-j},u_{T-j})$ with x_{T-j} given, is called a Bellman's equation.

The dynamic programming problem above is usually simplified by assuming that the return functions and transition equations are time invariant:

$$r_t(x_t,u_t) = ß^t r(x_t,u_t), \quad 0 < ß < 1$$

$$g_t(x_t,u_t) = g(x_t,u_t),$$

where ß is the discount factor expressing time preferences.
A current value function is then defined as

$$v_{j+1}(x_{T-j}) = ß^{j-T} W_{j+1}(x_{T-j}),$$

and Bellman's equation becomes:

$$v_{j+1}(x_{T-j}) = \max\{r(x_{T-j},u_{T-j}) + ßv_j(x_{T-j+1})\},$$

which often is more simply written (Myers, 1990) as

$$v_t(x_t) = \max\{r(x_t,u_t) + ßv_{t+1}(x_{t+1})\}.$$

The dynamic programming replacement problem is usually formulated as a cost minimization problem over a finite (and often short) planning horizon. The length of the planning horizon, the initial age of the machine, and a maximum useful life of the machine (all in years) must be set initially. The state variable is the age of the machine in the current year. It is usually assumed that replacement, if it occurs, occurs at the beginning of the year. Hence the transition equation is:

$$x_{t+1} = \left| \begin{array}{ll} x_t + 1, & \text{if the machine is kept at time } t \\ 1, & \text{if replacement occurs at time } t \end{array} \right| .$$

Necessary data include:

$c(x_t)$ = the annual cost of operating a machine which is of age x_t at the start of year t,

$t(x_t)$ = the trade-in value received when a machine which is of age x_t is traded for a new machine,

$s(x_T)$ = the salvage value received for a machine that has just turned age x_T at the end of the planning horizon, T ($s(x_T)$ may equal $t(x_T)$), and p = the price of a new machine (of age 0).

The current value function, $v_t(x_t)$, is the minimum cost of owning and operating a machine from year t through year T, starting year t with a machine just turned age x_t. It may be expressed as the Bellman's equation:

$$v_t(x_t) = \min \left| \begin{array}{l} \text{Buy: } p - t(x_t) + c(0) + v_{t+1}(1) \\ \text{Keep: } c(x_t) + v_{t+1}(x_t + 1) \end{array} \right| .$$

Example replacement problems solved with dynamic programming can be found in Bellman and Dreyfus (1962), Cooper and Cooper (1981), Dreyfus and Law (1977), Gillet (1976), and Winston (1987). The same texts also present formulations for extensions to the simple replacement problem that include the possibilities of overhauling a machine rather than replacing it, replacing a machine with a leased rather than purchased machine, technological change, and stochastic outcomes. Larson and Casti (1978) also present a formulation that includes the possibility of replacing with a used machine. These extensions are similar in structure to the simple replacement problem, but include more state variables, more control variables, and more comparisons of alternative policies in each period.

Dynamic programming has one major deficiency as a numerical optimization procedure that becomes quite evident in machinery replacement problems. As the number of states and possible state values becomes even moderately large, the number of calculations and amount of computer memory required by dynamic programming problems increase geometrically and can be enormous. Richard Bellman referred to this difficulty as "the curse of dimensionality". Replacement problems for agricultural machinery are particularly troublesome, because the machinery often stays productive for 15 years or more. For example, a recent combine replacement study by Weersink and Stauber (1988) that allowed for 6 possible prices, 16 possible tax options, and 15 possible combine ages consisted of 1,440 (6 x 16 x 15) states. As a result, dynamic programming replacement models must be parsimonious in the number of state variables, control variables, and possible values for state and control variables.

Chapter 3

THE ANALYTICAL MODEL

State Variables and Control Variables

The model used to analyze the conservation tillage adoption problem is an extension of the dynamic programming replacement model discussed in Chapter 2. The standard replacement model determines the optimal period to trade in a used machine and purchase a new, but otherwise identical machine. The replacement model is first extended by considering the replacement of two machines, a tractor and a planter, and by considering their replacement with an alternative tractor and planter. A no-till planter is the key machinery component of a no-till system, so replacement of a conventional planter with a no-till planter represents adoption of no-till technology. Tractor replacement with two possible sizes is included because most budget analyses of conventional tillage and no-till systems assume a smaller and less costly tractor for the no-till system than for the conventional tillage system. A second extension of the replacement model is to consider the possibility of renting a planter. Third, costs for the no-till system are varied according to years of experience with that technology. These extensions are sufficient for the deterministic analysis. The additional extensions required for stochastic analysis are discussed in the last section of this Chapter.

Since the dynamic programming model must be kept small enough that it can be solved, state variables and control variables are restricted to those that most affect the adoption decision. The state variables included in the deterministic model are:

1) an ownership variable indicating which machines are owned at the start of each crop season (5 possibilities are allowed);
2) age (in years) of the planter (17 years are allowed);
3) age (in 400 hour units) of the tractor (34 units are allowed); and
4) levels of experience with a no-till planter (4 levels are allowed).

The ownership variable determines which control variables may be considered in each year, including the possible sale of machinery. The ages of the planter and tractor determine repair costs and salvage or trade-in value. The tractor's age is measured in 400 hour units, rather than years, because usage per year will vary according to whether a conventional tillage or no-till system is selected. Usage of the conventional tillage system for 600 acres of corn and soybeans is approximately 800 hours per year. Usage for the no-till system in the same situation is approximately 400 hours per year. Therefore, the tractor ages by two 400-hour units per year when conventional tillage is selected and by one 400-hour unit per year when the no-till system is selected. The combination of four state variables with the number of levels indicated for each state variable result in a total number of 14,450 states to be considered each year, with one policy determined for each state.

The control variables included in the deterministic model are:

1) use of a conventional tillage or no-till planter;
2) rent, purchase, keeping, or replacement by purchase of the planter;

3) keeping or replacement by purchase of the tractor; and

4) choice between a large or small tractor.

Selection of a conventional tillage planter implies that primary tillage operations with a moldboard plow and secondary tillage operations with a tandem disk are performed before planting and that row cultivation is performed after planting. The preplant plow and disk operations are needed to obtain an adequate crop stand with a conventional tillage planter. Row cultivation is a cost-effective means of controlling weeds, but is difficult to do with the relatively heavy crop residues found on the soil surface under a no-till system. Therefore, when the conventional planter is selected, the costs of the plow, disk, and row cultivator operations are included. Other cost adjustments for the alternative tillage systems are explained in Chapter 4.

All of the control variables are binary. Hence, the alternative choices or policies are a combination of options to purchase, sell, rent, or keep machinery. When only the large tractor is owned there are 10 policy options (Table 3.1). When only the small tractor is owned there are 8 policy options (Table 3.2). When the large tractor and conventional planter are owned and renting options are limited to renting a planter for the entire 600 acres there are 14 policy options (Table 3.3). The addition of options to rent a no-till planter on 60, 120, or 240 acres while keeping the conventional planter add another 6 policy options (Table 3.4). When the large tractor and no-till planter are owned there are 13 policy options (Table 3.5). Finally, when the small tractor and no-till planter are owned there are 11 policy options (Table 3.6). This means that a total of 18 policy options are

Table 3.1 Control Options When a Large Tractor but No Planter is Owned

1. Buy and use the conventional planter.

2. Buy and use the no-till planter.

3. Replace the large tractor, then buy and use the conventional planter.

4. Replace the large tractor, then buy and use the no-till planter.

5. Replace the large tractor with the small tractor, then buy and use the no-till planter.

6. Rent and use the conventional planter.

7. Rent and use the no-till planter.

8. Replace the large tractor, then rent and use the conventional planter.

9. Replace the large tractor, then rent and use the no-till planter.

10. Replace the large tractor with the small tractor, then rent and use the no-till planter.

Table 3.2 Control Options When a Small Tractor but No Planter is Owned

1. Buy and use the no-till planter.

2. Replace the small tractor, then buy and use the no-till planter.

3. Replace the small tractor with the large tractor, then buy and use the conventional planter.

4. Replace the small tractor with the large tractor, then buy and use the no-till planter.

5. Rent and use the no-till planter.

6. Replace the small tractor, then rent and use the no-till planter.

7. Replace the small tractor with the large tractor, then rent and use the conventional planter.

8. Replace the small tractor with the large tractor, then rent and use the no-till planter.

Table 3.3 Control Options when a Large Tractor and Conventional Planter are Owned and Renting Options are Limited

1. Replace and use the conventional planter.

2. Replace the conventional planter with the no-till planter and use the no-till planter.

3. Replace the large tractor and use the conventional planter.

4. Replace and use the large tractor and the conventional planter.

5. Replace the large tractor, replace the conventional planter with a no-till planter, then use the no-till planter.

6. Replace the large tractor with the small tractor and the conventional planter with the no-till planter, then use the no-till planter.

7. Sell the conventional planter, then rent and use a conventional planter.

8. Sell the conventional planter, then rent and use a no-till planter.

9. Replace the large tractor, sell the conventional planter, then rent and use a conventional planter.

10. Replace the large tractor, sell the conventional planter, then rent and use a no-till planter.

11. Replace the large tractor with the small tractor, sell the conventional planter, then rent and use a no-till planter.

12. Keep the conventional planter, but rent and use the no-till planter.

13. Replace the large tractor, keep the conventional planter, then rent and use the no-till planter.

14. Keep and use the large tractor and conventional planter.

Table 3.4 Additional Renting Options when a Large Tractor and Conventional Planter are Owned

1. Keep the large tractor and conventional planter, but rent the no-till planter on 60 acres (of both corn and soybeans).
2. Keep the large tractor and conventional planter, but rent the no-till planter on 120 acres.
3. Keep the large tractor and conventional planter, but rent the no-till planter on 240 acres.
4. Replace the large tractor, keep the conventional planter, and rent the no-till planter on 60 acres.
5. Replace the large tractor, keep the conventional planter, and rent the no-till planter on 120 acres.
6. Replace the large tractor, keep the conventional planter, and rent the no-till planter on 240 acres.

Table 3.5 Control Options when a Large Tractor and No-till Planter are Owned

1. Replace the no-till planter with the conventional planter, then use the conventional planter.

2. Replace and use the no-till planter.

3. Replace the large tractor and use the no-till planter.

4. Replace the large tractor with the small tractor, then use the no-till planter.

5. Replace the large tractor, replace the no-till planter with the conventional planter, then use the conventional planter.

6. Replace and use the large tractor and no-till planter.

7. Replace the large tractor with the small tractor, replace the no-till planter, then use the no-till planter.

8. Sell the no-till planter, then rent and use a conventional planter.

9. Sell the no-till planter, then rent and use a no-till planter.

10. Replace the large tractor, sell the no-till planter, then rent and use a conventional planter.

11. Replace the large tractor, sell the no-till planter, then rent and use a no-till planter.

12. Replace the large tractor with a small tractor, sell the no-till planter, then rent and use a no-till planter.

13. Keep and use the large tractor and no-till planter.

Table 3.6 Control Options when a Small Tractor and No-till Planter are Owned

1. Replace and use the no-till planter.
2. Replace the small tractor with a large tractor, then use the no-till planter.
3. Replace the small tractor, then use the no-till planter.
4. Replace the small tractor with a large tractor and the no-till planter with a conventional planter, then use the conventional planter.
5. Replace the small tractor with a large tractor, replace the no-till planter, and use the no-till planter.
6. Replace and use the small tractor and no-till planter.
7. Sell the no-till planter, then rent and use a no-till planter.
8. Replace the small tractor with a large tractor, sell the no-till planter, then rent and use a conventional planter.
9. Replace the small tractor with a large tractor, sell the no-till planter, then rent and use a no-till planter.
10. Replace the small tractor, sell the no-till planter, then rent and use a no-till planter.
11. Keep and use the small tractor and no-till planter.

considered for each of 136 combinations of tractor age and years of experience when only a tractor is owned. A total of 38 or 44 policy options are considered for each of 2,312 combinations of planter age, tractor age, and years of experience when both a tractor and a planter are owned.

Other potential state and control variables are ignored. In particular, state variables describing soil qualities are not included, in contrast to Smith (1986) in which depth of soil layers is included as a state variable in order to consider soil erosion effects on crop yields and revenues. This model ignores soil erosion effects on crop yields because their magnitude is estimated to be negligible for 100 years on the soils assumed for this analysis (see Chapter 5) and the discounted value of any effects more than 100 years into the future is small. Second, it is assumed that all purchases are made with equity capital, rather than financed with borrowed capital. Allowing purchases with borrowed capital would increase the number of total permutations of state variables by at least 4 times. One state variable with 2 levels would be needed to indicate whether loan repayments have to be made that year for the planter[1]. Another state variable with at least 2 levels would be needed to indicate whether loan repayments have to be made that year for the planter[2]. Tax considerations are ignored because another

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[1] This assumes either that all payments are equal or only a new planter is purchased. If payments are not equal, but a new planter is purchased, the age of the planter can be used to determine the year within the payment schedule. If neither of these conditions are met, another level would be needed for each year in the payment schedule.

[2] This assumes that all payments are equal. Otherwise, another level must be added for each year in the repayment schedule.

state variable would be required to keep track of tractor depreciation, and yet another state variable would be required if Section 179 expensing deductions were considered. Finally, long-term leasing of equipment is ignored because the economic differences between purchasing and long-term leasing depend on individual tax and financial constraint considerations that are ignored in this analysis[3].

Although it has often been argued that tax effects should be considered in machinery replacement analyses (Chisolm, 1974; Kay and Rister, 1976; Reid and Bradford, 1983; Weersink and Stauber, 1988), most economic analyses have indicated that the optimal replacement decision is not very sensitive to tax depreciation rules. The studies by Chisolm (1974), Kay and Rister (1976) and Reid and Bradford (1983) all indicated that only investment tax credits (discontinued in 1987) have a large effect on the optimal timing of replacement. An exception is the study of combine replacement by Weersink and Stauber (1988) which found that lengthening the depreciation period beyond 5 years greatly affected the optimal year of replacement. However, Kay and Rister (1976), Reid and Bradford (1983) and Perry and Nixon (1991) all argue that changes in repair costs and remaining values are much more important than changes in tax depreciation schedules in determining optimal replacement policies. Therefore, it is reasonable to assume that the effect of tax deductions on expenses is approximately equal for all types of expenses

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[3] Consideration of financial constraints would either require entirely arbitrary constraints or expanding the dynamic programming model to include the whole-farm. A whole-farm model would limit or prevent the consideration of other adoption issues due to the limited computer capacity to handle additional dimensions in a dynamic programming problem.

and that any possible bias in the optimal adoption strategies caused by ignoring taxes is probably small.

Some important simplifying assumptions must be made to leave out other control variables. Acreage is held fixed at 400 acres of corn and 200 acres of soybeans. This corresponds to a corn-corn-soybeans rotation, which is common in southern Michigan. Quantities of seed, fertilizer, and pesticide inputs are fixed at levels recommended by the Michigan State Cooperative Extension Service for each tillage system. Static economic analyses typically allow one or more of these inputs and/or the crop mix to vary. However, acreage for each crop often is constrained by ASCS guidelines for participation in commodity price support programs, competition for fixed resources (e.g. labor) by other farm enterprises, or feed requirements for farm livestock enterprises. Pesticide quantities are legally constrained by label directions[4], and seed and fertilizer quantities are usually set according to standard agronomic recommendations. Another reason for fixing quantities of seed, fertilizer, and pesticides is that few agronomic studies in Michigan have varied tillage practice and these quantities in multifactorial experiments, so there is little scientific basis for estimating responses to changes in input quantities.

Several features in the model reflect agricultural and engineering constraints. The model includes a choice between a moderately large tractor of 140 PTO horsepower and a relatively small tractor of 85 PTO

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[4] Criminal penalties for not following pesticide labels for corn and soybeans are not yet common, but civil suits are increasing in frequency. Also the manufacturer makes no promise that non-labelled doses are effective or safe to other crops, which often is an effective deterrent.

horsepower. The large tractor is initially owned because it is assumed that conventional tillage and planting have been practiced before the planning horizon starts and the power of the small tractor is inadequate to pull a moldboard plow large enough to complete plowing in a timely manner[5]. Whenever the large tractor is owned, using either the conventional or no-till planters is considered. However, when the small tractor is owned, only the no-till planter is considered, because the conventional planter does not work effectively unless the soil has been plowed and the small tractor cannot pull the plow.

The model assumes that all machinery decisions are made before the crop season begins. For corn and soybeans in Michigan, this means that all machinery decisions are made before May 1, when it usually is desirable to plant (Neild and Newman, 1986). Actual planting dates depend on soil moisture, soil temperature, and the scheduling of pre-plant tillage operations. Three different scenarios for the proportion of acreage that is moldboard plowed in the fall are considered: 45%, 70%, and 100%[6]. Inability to complete plowing in the fall tends to retard planting in the spring, and thereby reduce crop yields. Farmers who are generally able to complete less of their plowing in the fall than their neighbors, due to less harvesting capacity or available time

[5] Hunt (1983) and Bowers (1987) provide good explanations of power requirements for field operations, and appropriate sizing of tillage and planting equipment. Chapter 5 also provides more explanation.

[6] The 45% and 70% proportions are based on crop progress reports for NE Indiana by the Indiana Crop and Livestock Reporting Service. Reported proportions for 1978-90 were sorted according to magnitude. The average of the lowest 7 reports is 45% and the average of the highest 6 reports is 70%. The overall average proportion is 58% for 1978-1990.

during the fall, will therefore be more inclined to adopt the no-till technology.

Modeling of Learning Curve Effects

The model assumes that production costs for the no-till technology are higher than their long-term average in the first year of adoption and fall with cumulative experience with that technology. This is consistent with the empirical evidence for learning curves in manufacturing processes (Mahd and Pindyck, 1989). The representative farmers are assumed to be fully experienced in using conventional tillage, so production costs for conventional tillage do not change with experience.

It is assumed that costs for herbicide, fuel and oil, and labor are sensitive to years of experience with no-till technology. Repair costs for the planter and tractor also are assumed to be sensitive to years of experience with no-till. Herbicide costs are expected to be initially higher for no-till because herbicide effectiveness varies with the timing of applications and other variables. Until no-till adopters have learned how to maximize the effectiveness of their herbicide applications, it is expected that they will have to repeat some applications in order to obtain acceptable weed control. Fuel, oil, tractor repairs, and labor costs increase if field operations have to be repeated or when field efficiency is reduced. No-till planter repair costs also increase if any replanting is needed, or if inexperienced farmers use them in ways for which they were not designed.

Three different learning curves are considered in the analyses of optimal adoption strategies. The 20% learning curve raises these costs by 20% in the first year of adoption, 14% in the second year of adoption, and 7% in the third year of adoption. The 10% learning curve reduces each of these cost factors by one-half. A zero learning curve, for which all production costs are insensitive to years of experience also is considered. Based on the estimate by Lichtenberg (1988) that average internal adjustment costs for replacement investment are 21% of the investment amount, the 20% learning curve is assumed for most of the analyses of optimal adoption strategies.

This very simple model of learning curve effects is used because there is a lack of empirical cost data regarding learning curves in US agriculture and because dimensionality constraints limit learning curve effects to only four levels. According to Jerry Grigar, SCS state agronomist and no-till farmer (personal communication, 1991), no-till farmers probably experience learning curve problems over at least five years. Also, the learning curve effect on costs for no-till technology probably does not decline linearly, because each year presents a different set of problems. A more likely functional form would be a reverse sigmoid curve, falling slowly at first, then falling quickly, and falling slowly again after several years of experience. However, the four levels of experience included in the dynamic programming model cannot represent a sigmoid curve very well, so a simple, nearly linear relationship is used. This at least provides a preliminary indication of learning curve effects on the optimal timing of adoption decisions.

Length of the Planning Horizon

Numeric dynamic programming optimizes an objective function over a finite time horizon. Solutions to dynamic programming replacement models therefore differ from solutions of methods that optimize over an infinite time horizon, but approach the same solutions as the time horizon approaches infinity. Modigliani (1952, p. 482) proposed an appropriate criterion for determining the best length of the planning horizon. He suggested that,

> "The problem of choosing the plan that will maximize the outcome of the firm's activity can be reduced logically to the problem of solving a system of simultaneous equations involving all future parameters and moves. This system, however, needs to be 'solved' only with respect to the first move."

Therefore the appropriate length of the planning horizon is the time for which plans must be made in order to arrive at the correct decision for the first period.

According to Boussard (1971), such a planning horizon may not exist for objective functions that maximize the discounted value of consumption over time. Boussard also claims that for problems which include long-lived durables with small salvage values (e.g. a machinery replacement problem), any planning horizon that satisfies Modigliani's criterion will tend to be lengthy. Boussard shows that a planning horizon exists that will satisfy Modigliani's criterion when the objective function is the maximization of terminal period wealth, and argues that this planning horizon will be shorter than that for an objective function with discounting. However, in order to maximize terminal period wealth in a dynamic programming problem, wealth would have to be included as another state variable, and many discrete levels of wealth would have to be included to minimize errors due to approximating a continuous function with discrete values. Therefore, an objective function that discounts future values is preferred to one that maximizes terminal period wealth for the machinery replacement problem.

Boussard (1971) also suggests searching for the planning horizon that satisfies Modigliani's criterion by comparing first period outcomes as the length of the planning horizon is increased and stopping when first-period results become insensitive to further increases in the length of the planning horizon. Kwack (1991) applied this criterion to a dynamic programming machinery replacement problem and found significant differences between the results for planning horizons of 15, 20, and 25 years. However, Kwack chose a 20-year planning horizon due to computer memory constraints.

Boussard's rule is used to set the length of the planning horizon for this analysis. The length of planning horizon that satisfied this rule was found to vary according to the choice of discount rate. With a 3% discount rate, the dynamic programming results sometimes changed as planning horizons were varied up to 60 years, so an 80-year planning horizon was finally used. With a 6% discount rate, a 60-year planning horizon was found to be adequate. Finally, with a 9% discount rate, a 50-year planning horizon was found to be sufficient. The length of these planning horizons also ensured consistency in the optimal policies for years 2-16.

Formulation of the Deterministic Model

The problem is to minimize:

$$V(\Omega_t, KT_{it}, KP_{jt}, X_t) = \sum_{t=1}^{T} \text{ß}^{t-1}\{PT_{it}(\Omega_t) + PP_{jt}(\Omega_t) - ST_i t(\Omega_t, KT_{it}) - SP_{jt}(\Omega_t, KP_{jt}) + [CT_{ijt}(\Omega_t, KT_{it} + CP_{jt}(\Omega_t, KP_{jt})]*CX(X_t) - R_{jt}(\Omega_t)\},$$

subject to the following laws of motion:

$$ST_{i,t+1}(KT_{i,t+1}) = \left| \begin{array}{ll} \delta_{i1}*L_i*[H_i(1)]\hat{\ }\delta_{i2} & \text{if } ST_{it}(KT_{it}) > 0 \\ \delta_{i1}*L_i*[H_i(KT_{it})+H_i(1)]\hat{\ }\delta_{i2} & \text{if } ST_{it}(KT_{it}) = 0 \end{array} \right|$$

$i=1,2,$

$$SP_{j,t+1}(KP_{j,t+1}) = \left| \begin{array}{ll} \delta_{j1}*L_j*[H_j(1)]\hat{\ }\delta_{j2} & \text{if } SP_{jt}(KP_{jt}) > 0 \\ \delta_{j1}*L_j*[H_j(KP_{jt})+H_j(1)]\hat{\ }\delta_{j2} & \text{if } SP_{jt}(KP_{jt}) = 0 \end{array} \right|$$

$j=1,2,$

$$CT_{ij,t+1}(KT_{i,t+1}) = \left| \begin{array}{ll} \theta_{i1}*L_i*[H_i(1)]\hat{\ }\theta_{i2} & \text{if } ST_{it}(KT_{it}) > 0 \\ \theta_{i1}*L_i*[H_i(KT_{it})+H_i(1)]\hat{\ }\theta_{i2} & \text{if } ST_{it}(KT_{it}) = 0 \end{array} \right|$$

$i=1,2,\ j=1,2,$

$$CP_{j,t+1}(KP_{j,}t_{+1}) = \left| \begin{array}{ll} \theta_{j1}*L_j*[H_j(1)]\hat{\ }\theta_{j2} & \text{if } SP_{jt}(KP_{jt}) > 0 \\ \theta_{j1}*L_j*[H_j(KP_{jt})+H_j(1)]\hat{\ }\theta_{j2} & \text{if } SP_{jt}(KP_{jt}) = 0 \end{array} \right|$$

$j=1,2,$

$$KT_{i,t+1} = \left| \begin{array}{ll} 1 & \text{if } ST_{it}(KT_{it}) > 0 \\ KT_{it} + 1 & \text{if } ST_{it}(KT_{it}) = 0 \end{array} \right|$$

$i=1,2,$

$$KP_{j,t+1} = \left| \begin{array}{ll} 1 & \text{if } SP_{jt}(KP_{jt}) > 0 \\ KP_{jt} + 1 & \text{if } SP_{jt}(KP_{jt}) = 0 \end{array} \right|$$

$j=1,2,$

$$X_{t+1} = \left| \begin{array}{ll} X_t & \text{if } R_{2t} = 0 \\ X_t + 1 & \text{if } R_{2t} > 0 \end{array} \right|,$$

subject to initial levels for KT_i, KP_j, and X_j, and subject to the terminal condition:

$$V_{T+1}(\Omega_{T+1},KT_{i,T+1},KP_{j,T+1},X_{T+1}) = -ST_{i,T+1}(KT_{i,T+1}) - SP_{j,T+1}(KP_{j,T+1}),$$

$$i=1,2,\ j=1,2,$$

where:

Ω_t = the ownership state in year t;

KT_{it} = the age of tractor i in year t, i=1,2;

KP_{jt} = the age of planter j in year t, j=1,2;

X_t = years of experience with planter 2 before year t;

β = a discount factor, $0<\beta<1$;

PT_{it} = the price paid for tractor i if purchased in year t, i=1,2;

PP_{jt} = the price paid for planter j if purchased in year t or the rental cost of planter j if rented in year t, i=1,2;

ST_{it} = the salvage or trade-in value of tractor i when it is KT_{it} years old if it is sold in year t, i=1,2;

SP_{jt} = the salvage or trade-in value of planter j when it is KP_{jt} years old if it is sold in year t, j=1,2;

CT_{ijt} = repair costs for tractor i when it is KT_{it} years old in year t if it is used in year t with planter j and associated implements, i=1,2, j=1,2;

CP_{jt} = repair costs for planter j when it is KP_{jt} years old in year t if it is used in year t, plus variable input costs associated with use of planter j that are affected by CX_t (herbicide, fuel, labor), j=1,2;

CX_t = a cost factor that depends on years of experience before year t with planter 2;

R_{jt} = gross revenues for 400 acres of corn and 200 acres of soybeans if planted with planter j in year t, minus variable costs that are not affected by CX_t, and minus constant fixed costs, j=1,2;

δ_{i1}, δ_{i2} = repair cost parameters for tractor i, i=1,2;

L_i = the list price of tractor i, i=1,2;

H_i = cumulative hours of use of tractor i after KT_{it} years (divided by 1000), i=1,2;

θ_{j1}, θ_{j2} = repair cost parameters for planter j, j=1,2;

L_j = the list price of planter j, j=1,2; and

H_j = cumulative hours of use of planter j after KP_{jt} years (divided by 1000), j=1,2.

The control variables, which depend on the ownership state in year t, are the selection of planter and tractor in year t and the choices between buying, renting, selling, and keeping planters and tractors in year t (listed in Tables 3.1 through 3.6).

Formulation of the Stochastic Model

The stochastic model is similar to the deterministic model, except that crop yields and crop prices become stochastic variables and the objective function is changed to the maximization of an expected utility function. Since corn and soybean prices exhibit high variation but strong serial correlation from one year to the next, they are included as a stochastic state variable and a separate optimal policy is determined for each price state outcome. Thirty-three crop yield outcomes for corn and soybeans grown with both conventional tillage and no-till are included in the model. However, the crop yield outcomes are assumed to be independent from one year to the next and only become known after machinery decisions are made, so an optimal policy choice is made for the entire set of crop yields, not for each crop yield.

Other possible sources of variation in net returns from corn and soybean production had to be ignored due to computer capacity and expense constraints. It would be desirable to include the proportion of fall plowing that is completed in the fall as an additional stochastic state variable because it affects both the mean and variance of crop yields and is known early enough that farmers can respond by changing machinery before planting. However, this was not feasible due to the limited computer memory addressing capacity of Microsoft FORTRAN 5.1, and the extreme expense of obtaining solutions for the stochastic model on the mainframe computer at Michigan State University.

Michigan corn and soybean prices exhibit such a high degree of serial correlation that they needed to be considered as a stochastic state variable for which probabilities of price states in the current period are determined by price state outcomes in the previous period. When the Michigan annual average corn prices for the 1956-1990 marketing years (Appendix B) were regressed on the previous years' corn prices, the resulting t-statistic for the lagged corn price was 7.33. When the Michigan annual average soybean prices for the 1956-1990 marketing years were regressed on the previous years' soybean prices, the resulting t-statistic for the lagged soybean price was 6.10[7] Therefore, a Markovian probability matrix was estimated, based on the 1955-1990 price data (Appendix B). Levels of the price state variable were limited to combinations of three levels of corn prices and three levels of soybean prices due to computer capacity constraints.

The combination of 3 price levels for corn and 3 price levels in soybeans results in a joint distribution of 9 levels, but combinations of high corn and low soybean prices and vice versa are not observed in the 1956-1990 Michigan data. This is to be expected, since Michigan corn and soybean prices are highly correlated. A regression of Michigan corn prices on soybean prices for 1955-1990 results in a t-statistic of 7.78 for the soybean price[8]. Therefore, the 9 price levels for the joint distribution were pared to 7 levels. Transition probabilities for the Markovian probability matrix (Table 3.7) also were determined directly from the 1956-1990 Michigan price data. Some adjustments were made to the empirical transition probabilities (Appendix B), since a sample of 36 observations can only provide a crude indication of movements between 7 price states.

Crop price distributions were assumed to be independent of the crop yield distributions. Michigan soybean price data do exhibit a statistically significant negative relationship with Michigan average soybean yields. Michigan corn price data also exhibit a negative relationship with Michigan average corn yields, but the effect is not

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[7] These regressions were performed using ordinary least squares estimation with the SHAZAM econometrics program, Ver. 6.2 (White, 1990).

[8] Ibid.

statistically significant at a 5% level of error. However, the magnitude of even the soybean yield effect on soybean price is small in comparison with the differences between the three soybean price levels. Furthermore, below-average Michigan corn and soybean yields during the period 1956-1990 are associated with declines in their price levels about as often as they are associated with increases in their price levels, and similarly for above-average Michigan corn and soybean yields. Therefore, probabilities for the 7 joint price levels were assumed to be independent of crop yields.

Table 3.7 Markovian Matrix of Price State Probabilities, Corresponding to the Historical Mean Prices.

If Previous Price State was:	Probability of Each Current Price State Is: 1	2	3	4	5	6	7
1	0.70	0.10	0.08	0.12	0.0	0.0	0.0
2	0.10	0.23	0.22	0.15	0.15	0.0	0.15
3	0.22	0.18	0.40	0.20	0.0	0.0	0.0
4	0.08	0.20	0.10	0.40	0.07	0.07	0.08
5	0.18	0.10	0.0	0.15	0.20	0.20	0.17
6	0.15	0.0	0.15	0.15	0.15	0.15	0.25
7	0.0	0.0	0.0	0.05	0.05	0.20	0.70

Crop yields do not exhibit significant serial correlation once technological trends are removed (see Chapters 4 and 5) since weather during the crop season is essentially independent from one year to the next[9]. Therefore it is assumed that the crop yield variable is independent from one year to the next. Each of the 33 crop yield outcomes is given an equal probability of 3.03% because each is determined from a different year of climatic data (see Chapter 4).

The stochastic problem is to maximize:

$$V(\Omega_t, KT_{it}, KP_{jt}, X_t, \psi, \alpha_t) = E\{\sum_{t=1}^{T} \beta^{t-1} U[-PT_{it}(\Omega_t) - PP_{jt}(\Omega t) + ST_{it}(\Omega_t, KT_{it}) + SP_{jt}(\Omega_t, KP_{jt}) - [CT_{ijt}(\Omega_t, KT_{it}) + CP_{jt}(\Omega_t, KP_{jt})] * CX(X_t) + R_{jt}(\Omega_t, \psi, \alpha_t)]\},$$

subject to the same laws of motion and terminal condition as in the deterministic model, but also subject to:

$\alpha_{t+1} = g(\alpha_t)$;

where, in addition to the previous definitions:

$U[\bullet] = \sum_{j=1}^{33} \sum_{k=1}^{7} p_j * p_{kt} * ([\bullet]^{(1-r)})/(1-r)$;

r = a relative risk aversion coefficient;

ψ = the j=33 possible outcomes for crop yield;

p_j = the probability of each crop yield outcome;

α_t = the stochastic outcome for prices in year t from a probability distribution of k=7 possible outcomes.

p_{kt} = the probability of each crop price state in year t, given the price state outcome in period t-1.

The form of the utility function U reflects constant partial relative risk aversion (CPRRA). This functional form implies that risk

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[9] An exception might be trends caused by global warming. However, the inability of scientists to agree that global warming trends even exist shows that weather trends across years are difficult to detect.

aversion declines as annual net income rises (Chavas and Holt, 1990). It is a variation of constant relative risk aversion (CRRA) for which risk aversion falls as accumulated wealth rises. The CPRRA form is used despite empirical evidence by Pope and Just (1991) that rejects the CPRRA and constant absolute risk aversion (CARA) forms in favor of the CRRA form of risk aversion because of dimensionality constraints in the stochastic dynamic programming model. Using the CRRA form of risk aversion would require an additional state variable for levels of wealth that would have to cover a wide range of possible values. Since empirical data to support particular expected utility forms and risk aversion parameters are scarce and inconsistent, and because strong theoretical arguments have been made by Jones and Ostroy (1984) and Baldwin and Meyer (1979) that risk aversion is much less important for irreversible investments than the flexibility to respond to new information, more is gained by being precise about costs, prices, and yields in the model than by using the CRRA expected utility form. Furthermore, analysis using the CPRRA form of expected utility will produce results that approximate those that would be obtained using the CRRA form.

One limitation of the CPRRA and CRRA forms of expected utility is that the income or wealth outcomes all must be positive. Otherwise, the utility function is not defined over the usual range of relative risk aversion coefficients ($0<r\leq 1$). Based on the possible ranges for crop prices, crop yields, production costs, and net cash outflows for machinery investments (see Chapter 4), negative net income outcomes do occur unless the farmer receives additional income. However, sources of

income other than net revenue from corn and soybean production are ignored in the model. Also, most U.S. farmers have enough access to credit or assets that they could liquidate if they have negative net income that it is reasonable to assume that their risk attitudes are based on ranges of net income outcome that are always positive. Therefore, a sufficient constant of $90,000 was added to revenue in the stochastic model to ensure that all net income outcomes were positive. The added constant makes expected utility-maximizing farmers act less risk averse than they would act if no constant were added.

The relative risk aversion coefficients used in the stochastic analysis were 1.0, 0.5, and 0. Most macroeconomic estimates of relative risk aversion levels have been close to 1.0 (Blanchard and Fischer, 1989; Epstein and Zin, 1991). A risk aversion coefficient of one is computationally convenient because then the CPRRA function becomes a semi-log function. A farmer with a relative risk aversion coefficient of 1.0 is called moderately risk-averse in this analysis. However, estimates for U.S. farmers (Alderfer, 1990; Lins et al., 1981) suggest that many of them have risk aversion coefficients much less than one. A risk-aversion coefficient of 0.5 also is computationally convenient because then the CPRRA function becomes two times the square root of income outcomes. A farmer with a relative risk aversion coefficient of 0.5 is called slightly risk-averse in this analysis.

Chapter 4

METHODOLOGY

Crop Yields

The dynamic programming model selects an optimal strategy of machinery selection and acquisition over time for a specific set of crop yield, crop price and cost parameters. These parameters are chosen to represent typical corn and soybean enterprises in southern Michigan on a soil for which there is potential to increase profits in the long run by changing from conventional tillage to no-till corn and soybean production. Due to a relatively short growing season in this region, no-till is better adapted to well-drained soils, especially sands and sandy loams, than to poorly-drained soils that warm slowly in the spring. The increased soil moisture retention that no-till provides also is an asset on sandy soils, but may be a liability on poorly-drained soils. Parameters therefore are chosen to represent corn and soybean production on an Oshtemo sandy loam soil that is widespread in Kalamazoo, St. Joseph, and neighboring counties.

Corn, soybeans, and alfalfa are the dominant crops in this area of Michigan. Many farms also have dairy or other livestock enterprises. However, livestock and forage production enterprises are beyond the scope of this analysis. Therefore, the model does not attempt to represent a whole farm, although a few farms in this area do produce only corn and soybeans. The farm is assumed to produce 400 acres of corn and 200 acres of soybeans, grown in a corn-corn-soybeans rotation.

<u>Climate and Soils in S.W. Michigan</u>

The study area receives an average of about 34 inches of precipitation annually with monthly averages of about 3 inches or more from April through September (Table 4.1). These average precipitation amounts are more than adequate for the production of corn and soybeans (Shaw, 1988; Van Doren and Reicosky, 1987). However, several factors may cause growing corn and soybean crops to suffer from insufficient moisture, including: (1) temporal variance in rainfall distribution; (2) high precipitation runoff due to steep slopes, slow infiltration, and/or lack of surface crop residues; and (3) coarse-textured soils that allow much of the moisture from precipitation to drain below the root zone.

Table 4.1 Average Monthly Temperature and Precipitation, 1951-1980 at Kalamazoo, Michigan.

Month	Avg. daily maximum temp. (°F)	Avg. daily minimum temp. (°F)	Avg. no. of growing degree days*	Average Precip. (inches)
January	30.9	16.5	0	2.08
February	34.7	18.2	0	1.67
March	45.3	26.6	18	2.39
April	60.3	37.6	114	3.56
May	72.3	48.0	340	3.14
June	81.1	57.3	583	3.83
July	84.9	61.4	725	3.62
August	83.2	59.9	675	3.17
September	76.1	53.0	447	3.15
October	64.1	42.6	175	3.00
November	48.3	32.4	27	2.67
December	35.8	22.1	0	2.55
Year	59.7	39.6	3105	34.83

* Defined as the average of daily max. and min. temperatures minus 50° F., provided that this average daily temperature exceeds 50° F.

Source: Michigan Dept. of Agriculture, Climatology Program

Much of the cultivatible land in the study area has coarse-textured soils. The Soil Conservation Service (SCS) describes 40% of the non-urban land in Kalamazoo county and 81% of the non-urban land in St. Joseph county as being loamy sand or sandy loam (Austin, 1979; Cowan, 1983). Oshtemo sandy loam, Spinks loamy sand, and Hillsdale sandy loam are the principal soils in this group. Another 40% of the non-urban land in Kalamazoo county and 4% of the non-urban land in St. Joseph county is described as having well-drained loam soils. Kalamazoo loam, Riddles loam, and Schoolcraft loam are principal soils in this group. The SCS notes soil droughtiness and blowing or soil erosion concerns for over 70% of the soils in capability classes I-III (the principal agricultural soils) in the two counties.

The combination of well-drained, coarse-textured soils and susceptibility to soil erosion makes the no-till system appear to be an ideal choice for corn and soybean production in this region. In a ranking of various Corn Belt soils, Mannering and Amemiya (1987) classify the Oshtemo, Hillsdale, and Kalamazoo soils as all being "highly adapted by all standards" for no-till production. Indeed, the proportion of corn and soybean acreage planted with no-till systems has gradually increased to about 30% in Kalamazoo county and fluctuates between between 13% and 19% in St. Joseph county (SCS, Michigan, various years). This compares to the approximately 13% of corn and soybean acreage planted with no-till systems in the entire state in 1990 (SCS, Michigan, 1990).

Agronomic Studies of Crop Yields for Conservation Tillage Systems

Agronomic studies over about 30 years and in a variety of locations with a variety of soils have demonstrated that the relative yield advantage of alternative tillage systems depends on soil, weather, and pest conditions. Conventional tillage with a moldboard plow tends to produce substantially higher corn yields than a no-till system on poorly drained soils with a high clay content, whereas relative corn yields are reversed on well drained soils with a high sand content. Fewer tillage trials have been performed for soybeans than for corn, but the relative yield advantage for no-till on well-drained soils (Campbell et al., 1984) and disadvantage on poorly-drained soils (Gephardt and Minor, 1983; Brown et al., 1989) is similar to that of corn. Tables 4.2 and 4.3 show relative corn and soybean yields for tillage with moldboard plow and a no-till system on two soils in Ohio with contrasting drainage characteristics over a 20-year period.

However, the relative yield advantages of alternative tillage systems on well drained and poorly drained soils are seldom consistent from one year to the next. Weather conditions and weather-related pest conditions have caused the expected yield relationships to disappear or be reversed in some years. A prime example is the drought of 1988 when there often was not enough rainfall to make herbicides effective, so no-till crop yields were lower than conventional tillage yields despite having greater soil moisture holding capacity under no-till. Pest effects are beyond the scope of this analysis, but even assuming that pesticide applications provide effective pest control, the timing of

Table 4.2 No-till minus plowed corn yields (kg/ha), 1963-1983 5-year averages on Wooster and Hoytville soils in Ohio.

5-year period	Wooster silt loam Avg. Yield	No-till minus plowed yields* CC	CS	LSD	Hoytville silty clay loam Avg. Yield	No-till minus plowed yields* CC	CS	LSD
1963-67	6530	748	273	566	6910	-536	-301	425
1965-69	7350	805	840	633	6850	-977	-38	389
1967-71	7610	929	865	739	7610	-1090	-90	393
1969-73	8620	707	884	653	8115	-1230	-181	503
1971-75	8750	1620	1520	739	8560	-1350	-151	539
1973-77	8305	1500	580	684	8050	-801	-172	535
1975-79	8430	1130	1420	673	9570	-1291	-373	506
1977-81	8940	615	802	675	9130	-1480	-802	665
1979-83	8880	1270	1790	805	9070	-633	-133	745

* CC is continuous corn, CS is corn in a corn-soybean rotation, and LSD is the least significant difference at the 5% error level.
Source: Dick and Van Doren (1985)

Table 4.3 No-till minus plowed soybean yields (kg/ha), 1963-1983 5-year averages on Wooster and Hoytville soils in Ohio.

5-year period	Wooster silt loam Avg. Yield	No-till minus plowed yield	LSD*	Hoytville silty clay loam Avg. Yield	No-till minus plowed yield	LSD*
1963-67	1420	213	195	2100	-20	229
1965-69	1540	285	182	2590	-9	263
1967-71	1520	258	148	2780	-368	215
1969-73	1950	122	249	2470	-464	236
1971-75	2080	116	330	2540	-452	296
1973-77	2250	182	337	2500	-652	384
1975-79	2270	310	229	2710	-752	404
1977-81	2290	380	256	2530	-710	269
1979-83	2220	300	405	2660	-410	239

* LSD is the least significant difference at the 5% error level.
Source: Dick and Van Doren (1985)

weather events in relation to crop development often alters the relative yields of alternative tillage systems.

Effects of Soil Temperature on Corn and Soybean Growth

Tillage and planting systems are designed to place seeds in a favorable soil environment for germination and plant growth. According to Richey et al. (1977, p. 157), the primary requirements for successful planting are:

1. Soil dry enough to permit proper planter functions.
2. Adequate warmth and moisture for germination and early growth.
3. Minimum crusting impedance to emergence.

Richey et al. (1977) also assert that soil does not warm until it has dried. Moldboard plowing facilitates soil drying and warming by turning and loosening the soil, and by burying crop residues that shade the soil from the sun and reflect large amounts of solar radiation. In contrast, the no-till system does not disturb the soil before planting and insulates the soil with surface crop residues. Thus, experiments in Indiana on a variety of soils have consistently shown soil temperatures in the 8 weeks following corn planting to be around 2.5°C less for a no-till system than for a moldboard plow system (Richey et al., 1977). Other agronomic studies by Van Wijk et al. (1959), Burrows and Larson (1962), Allmaras et al. (1964), Johnson and Lowery (1985), and Bronson (1989) have documented temperature reductions due to surface mulches of 1-5° C. at depths of 5-10 cm. during the months of May and June.

Many of the same studies that documented soil temperature reductions due to surface mulch also reported that the lower soil temperatures reduced plant height and biomass production of corn in May and June. Controlled experiments by Allmaras et al. (1964), Walker (1969), Watts (1972), and Barlow et al. (1977) confirmed that soil temperature reductions as small as 1° C. within the range of 10° to 26° or 28° C. reduced dry weights, leaf lengths, leaf numbers, stem lengths, and root numbers of corn seedlings. According to Walker (1969), differences in plant dry weights were as much as 30 to 40% per 1° C. increment. Walker (1969) also documented reduction in the dry weight of corn roots due to soil temperature reductions.

Much of the reason for the sensitivity of corn seedlings to soil temperature is that the growing point of the corn plant remains below the soil surface until the sixth leaf fully emerges (Neild and Newman, 1986). In contrast, the growing tip of soybean plants rises above the soil surface as soon as the plants emerge. Hence, the influence of soil temperature on soybean plant growth is much less than for corn, and also is not as well documented. However, Earley and Cartter (1945) reported a strong effect of root temperatures on dry weight production of soybean tops and a smaller but consistent effect of root temperatures on dry weight production of soybean roots. Stone and Taylor (1983) reported very significant effects of soil temperature on rates of soybean taproot and lateral root extension. Meese et al. (1991) reported that no-till resulted in lower soil temperature, delayed soybean emergence, and lower soybean plant height at 6 weeks than for conventional tillage. Hesketh et al. (1973) also documented that soybean emergence is delayed by reduced temperatures. Other studies, such as Webber et al. (1987) and Lueschen et al. (1991), have documented reduced early growth of soybeans under no-till than under conventional tillage, but did not record soil temperatures.

Reduced early corn and soybean growth is not necessarily a problem. First, the magnitude of the effect of reduced soil temperature on corn and soybean growth depends on the absolute temperature level. Second, delayed phenological development allows more dry matter production within each growth stage, which tends to increase yields. Third, the timing of moisture and nutrient stresses with respect to phenological stages is critical, with crop yield being far more sensitive to such stresses during reproductive stages than to stresses during vegetative stages. Thus, delayed phenological development may help or hurt depending on whether these stresses and reproductive stages coincide. However, if the plant has not completed its development and attained physiological maturity before cold weather stops or slows further development, crop yield will be reduced by delayed development. Corn is particularly susceptible in the study area to frost damage if planted late. Since the average number of growing degree days during the average frost-free period (2600-2800) is about the same as the number of growing degree days required for a typical mid-season corn hybrid to reach maturity (2700), delayed corn planting often results in the corn not reaching full maturity before the first frost (Neild and Newman, 1986; Michigan Dept. of Agriculture, Climatology Program).

<u>Estimation of Crop Yields</u>

Crop yields for the stochastic dynamic programming model are estimated with modified versions of the CERES-MAIZE and SOYGRO crop growth simulation models. Yield estimates from these simulation models are used instead of actual crop yield data for several reasons. First, no long-term tillage studies have been conducted in the study area. The nearest long-term tillage studies are the experiments in Ohio on Wooster and Hoytville soils. At these locations, the growing season is longer, temperatures are generally higher, and the soils are not as sandy as those in the study area. Second, tillage studies in the study area have generally not included soybeans. Third, agronomic practices in long-term experiments are almost never constant. At a minimum, crop varieties and herbicides usually change as improved varieties and herbicides are developed. Fourth, soil fertility in experimental plots is almost always greater than in most farmers' fields because they have been carefully managed to keep soil fertility from being a limiting factor in agronomic experiments.

Finally, crop operations in experimental plots are usually completed in a single day, whereas crop operations in farmers' fields are often spread out over more than a week. Sometimes the operation dates for the experimental plots are closer to the optimal dates than operation dates in farmers' fields and sometimes operation dates for experimental plots are further from the optimal dates due to logistical problems. But yield results are almost always influenced by operation dates, which can be varied in the simulation models, but are historical facts in experimental results. The sensitivity of yield results to operation date is particularly great for alternative tillage systems. Reduced-tillage effects on crop growth vary according to the crop's phenological stage, and the phenological stage is a function of operation dates.

The CERES-MAIZE and SOYGRO crop growth simulation models share the same basic structure and input data requirements. Required input data include:

1. Various soil characteristics, especially characteristics that determine soil moisture conditions, initial soil nitrogen levels (not used by SOYGRO), and soil temperature.
2. Meteorological data, specifically daily maximum and minimum air temperatures, daily solar radiation, and daily precipitation.
3. Dates for the start of the simulation, planting, and irrigation treatments (if any).
4. Planting depth and plant spacing (plant population).
5. Crop-specific genetic parameters.

The CERES-MAIZE model also requires the following additional inputs in order to account for soil nitrogen and its effects on corn growth:

6. Residue amounts from the previous crop, plus depth of incorporation and the carbon to nitrogen (C:N) ratio for those residues.
7. Dates, amounts, formulations, and depths of nitrogen fertilizer applications.

The basic structure of the CERES-MAIZE and SOYGRO models (Jones and Kiniry, 1986; Wilkerson et al., 1983) is as follows:

1. A seed is planted on a specified date. The user also specifies soil characteristics, plant genetic characteristics, fertilizer treatments, irrigation treatments, and climatic data.

2. The model then steps through time in daily increments.
3. Temperature, photoperiod, and genetic parameters regulate the phenological development of the plant.
4. Phenological stages determine how biomass produced through photosynthesis is partitioned among plant organs.
5. Solar radiation and plant leaf area determine biomass (photosynthate) production.
6. Various stresses reduce the plant's capacity to produce biomass and partition it for maximum yield. These may include soil moisture, nitrogen or other nutrient deficiencies, temperature, soil bulk density, and soil pH.
7. The timing of these stresses relative to phenological stage has important effects on crop yield.
8. Temperature, photoperiod, and/or genetic parameters determine the maturity date.
9. Grain yield is determined by genetic parameters and how much biomass has been partitioned to the grain.
10. Soil moisture and nitrogen dynamics are determined by various processes throughout the simulation period (e.g. evaporation, transpiration, drainage, N uptake, mineralization, denitrification, leaching).

The CERES-MAIZE and SOYGRO models were selected in preference to other crop growth simulation models because they provide a more detailed accounting of phenological development and stresses encountered in each phenological stage than most other models (Kiniry, 1991; Jones et al., 1991) and because they only require moderate amounts of input data.

Accuracy in predicting phenological development is extremely important when analyzing variation in crop yields from year to year and for different planting dates. Also, the account of stress factor levels for each growth stage and the weekly accounts of soil moisture, soil nitrogen levels, and growth of various plant organs show the causes of high and low yields in specific cases.

The major deficiency of the CERES-MAIZE and SOYGRO models for this analysis is that they do not account for the major effects of no-till technology on corn and soybean plant growth and yields. The EPIC model (Sharpley and Williams, 1990) was considered for this analysis because it does account for tillage effects. However, accounting for phenological development is weak in the EPIC model because it attempts to portray the growth of any crop by varying a small number of parameters for a generic crop growth model. Furthermore, the complete source code and expert help were available for the CERES-MAIZE and SOYGRO models, but not for the EPIC model. Also, preliminary modifications to the CERES-MAIZE model to account for tillage effects had already been made by Frederic Dadoun[1] at Michigan State University, who provided the source code for the modifications. Therefore, Dadoun's modifications to the CERES-MAIZE model were refined and extended to the SOYGRO model. Also, modifications to account for soil temperature effects on root growth were added to both models. All modifications to the CERES-MAIZE and SOYGRO models are described and documented in Appendix C and listed in Appendices I and J.

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[1] Ph.D candidate, Crop and Soils Department.

Input Data for the Estimation of Crop Yields

The estimation of crop yields and all subsequent analysis is very sensitive to the input data selected for climate, soil, crop residues, fertilizer application, crop genetics, and operation dates. Thirty-three years of the climatic data required by the CERES-MAIZE and SOYGRO models were available in data files with the necessary format[2]. The required climatic data are the daily maximum temperature, minimum temperature, precipitation, and solar radiation levels. These data were available for Gull Lake, located in the northeast corner of Kalamazoo county, for 1984-1990, but solar radiation data at this site were not available for earlier years. Therefore, the Gull Lake data were combined with 1953-1978 data from East Lansing, Michigan, which is approximately 42 miles to the northeast of Gull Lake.

The CERES-MAIZE and SOYGRO models require several soil parameters to be specified for each soil layer. Reliable soil nitrogen data for an Oshtemo sandy loam (Table 4.4) were available from an agronomic study near Mendon, Michigan, in St. Joseph county. However, the sand content at the Mendon site was higher than usually found in Oshtemo sandy loam soils in the Gull Lake area, where the Oshtemo sandy loam and Kalamazoo loam are frequently intermixed and can be difficult to distinguish. Rainfed corn and soybean production, which is assumed in this analysis, is much more viable on the loamier soil of the Gull Lake area than on

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[2] Brian Baer, Dept. of Crop and Soil Sciences at Michigan State University, provided 1984-1990 data for Gull Lake. Alan Rotz, Dept. of Agricultural Engineering at Michigan State University, provided 1953-1978 data for the MSU Horticultural Farm in East Lansing. Climatic data for other years could have been used only after a very large investment of time or money.

the sandier soil of the Mendon area, where corn and soybeans are frequently irrigated. Therefore, soil moisture parameters (Table 4.5) were estimated from sand, silt, and clay content data found in the Oshtemo sandy loam profile provided with the EPIC model (Sharpley and Williams, 1990), which is more representative of the Oshtemo soil of the Gull Lake area. Estimation procedures for the soil moisture parameters are described in Ritchie et al. (1990).

Corn and soybean residue levels (Table 4.6) are used by CERES-MAIZE to calculate contributions to soil nitrogen from mineralization. The dry weight and carbon to nitrogen ratio of the residues determines how much nitrogen they potentially can provide. Corn and soybean surface residue levels also are used by the modified CERES-MAIZE and SOYGRO models to determine surface mulch effects on soil evaporation and temperature under the no-till system.

Table 4.4 Soil Nitrogen Inputs, Oshtemo sandy loam

Depth (cm.)	Initial Ammonium (ppm)	Initial Nitrate (ppm)	Bulk Density (g/cm^3)	Organic Carbon (%)	Soil pH
0 - 9	4.0	0.9	1.48	1.20	5.9
9 - 18	2.4	0.7	1.48	1.20	5.9
18 - 29	0.8	0.5	1.63	0.40	5.7
29 - 41	0.8	0.5	1.70	0.40	5.7
41 - 53	0.8	0.6	1.69	0.20	4.9
53 - 64	0.8	0.6	1.69	0.20	4.9
64 - 86	0.8	0.6	1.74	0.10	5.0
86 -106	0.8	0.6	1.74	0.10	5.6
106 -126	0.6	0.5	1.74	0.10	7.9
126 -146	0.5	0.3	1.74	0.10	7.9
146 -166	0.5	0.3	1.74	0.10	8.1

Table 4.5 Soil Moisture Inputs*, Oshtemo sandy loam

Albedo	0.16
Stage 1 Evaporation Coefficient	7.0
Drainage Coefficient	0.67
Runoff Curve Number	62.0

Depth (cm.)	Lower Limit (cm/cm)	Drained Upper Limit** (cm/cm)	Plant Extract. Moisture (cm/cm)	Saturated Content (cm/cm)	Root Distn. Factor
0 - 9	0.069	0.202	0.133	0.324	1.000
9 - 18	0.069	0.202	0.133	0.324	.763
18 - 29	0.127	0.248	0.121	0.298	.594
29 - 41	0.127	0.248	0.121	0.298	.413
41 - 53	0.128	0.246	0.118	0.305	.352
53 - 64	0.059	0.183	0.124	0.308	.279
64 - 86	0.055	0.161	0.106	0.308	.201
86 -106	0.039	0.111	0.072	0.292	.132
106 -126	0.039	0.111	0.072	0.292	.088
126 -146	0.039	0.111	0.072	0.292	.059
146 -166	0.039	0.111	0.072	0.292	.040

* These parameters are defined and their use is explained by Kiniry and Jones (1985) and Ritchie et al. (1990).

** Simulations started on March 1 with this soil moisture content.

Table 4.6 Corn and Soybean Residue Inputs

Input	After Corn	After Soybeans
Surface residue before plowing (dry, kg/ha)	5775	2370
C:N ratio of surface residue	50	25
Root residue	1500	1100
C:N ratio of root residue	40	25

Corn residue levels were set at the average levels reported by the CERES-MAIZE model in preliminary runs. The surface residue levels were estimated in an iterative procedure, based on the same climatic data, soil parameters, fertilizer applications, and genetic parameters that were used to estimate crop yields for the moldboard plow technology. An initial guess was made for continuous corn residue levels, based on results from the agronomic experiment at Mendon, Michigan. After adjusting for decomposition of corn residues over the winter[3], the average surface residue levels reported by CERES-MAIZE were found to be within 25 kg per hectare (0.4%) of the initial guess. All subsequent crop yield estimations for crops following corn in rotation assumed the adjusted average of 5775 kg per hectare of surface residue. The root residue level also was determined from root weight values reported by CERES-MAIZE in preliminary runs, and was adjusted for decomposition during the winter.

Soybean residue levels were calculated by multiplying the average seed yield from preliminary SOYGRO runs with the 33 years of climatic data by 1.5, the ratio of soybean straw to grain reported by Larson et al. (1978). Soybean root residue levels were directly estimated by SOYGRO. Both of these estimates were based on the assumption that soybeans were grown after 5775 kg per hectare of corn residue were incorporated by moldboard plowing. The same rate of residue decomposition over the winter was assumed for soybeans as for corn.

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[3] A loss of 23% of corn residues from harvest until March 1 was assumed, based on a 31% reduction reported by Greg and Black (1962) for sorghum stubble between harvest and April 12.

Fertilizer applied to corn consisted of a split application of 168 kg. per hectare (150 lb. per acre) of nitrogen. This is the rate recommended by Warncke et al. (1985) for a target yield of 130 bu. per acre in Michigan. Twenty kg. per hectare were applied in the form of ammonium nitrate at planting and 148 kg. per hectare were applied in the form of anhydrous ammonia in a sidedress application scheduled after crop emergence (see the discussion of operation dates below). The split application of nitrogen fertilizer is a common practice in the study area because it minimizes loss of soil nitrate due to leaching and denitrification before the corn plant can utilize it.

Parameters for the corn hybrid, Pioneer 3475, and a generic maturity-group 2 soybean variety were chosen for the analysis. Parameters for this corn hybrid and soybean variety are contained in genetic input files for the CERES-MAIZE and SOYGRO models. The Pioneer 3475 variety is commonly grown in the study area and has been used in many agronomic experiments. Pioneer 3475 also was chosen in preference to another common hybrid with a shorter maturity length, Pioneer 3780, after a preliminary analysis of both hybrids using the 33 years of climatic data indicated that hybrid 3475 had a significantly higher average yield and rarely provided a lower yield. The maturity-group 2 rating for soybean varieties is the one recommended for most of southern Michigan by extension agronomists (Vitosh et al., 1991).

However, when corn planting was delayed after Julian date 140 (May 20 in most years) and when soybean planting was delayed after Julian date 155 (June 4 in most years), shorter-season varieties were substituted for Pioneer 3475 and the maturity-group 2 soybean variety.

The shorter-season corn hybrid was Pioneer 3780 and the shorter-season soybean variety was a generic maturity-group 1 soybean variety. Substitution of shorter-season varieties allowed the crops to more fully mature before cold temperatures in the fall halted their development. The timing of the switch to shorter-season varieties was partly determined by experimenting with the CERES-MAIZE and SOYGRO models and partly determined in relation to published guidelines for optimal planting dates. Rotz et al. (1983) estimate that the expected yield for corn declines 1% per day as planting is delayed past May 13. Rotz et al. (1983) also estimate that the expected yield for soybean declines 1% per day as planting is delayed past May 20. Hence, a shorter-season corn hybrid is used when the expected yield loss due to late planting is at least 7%. and a shorter-season soybean variety is used when the expected yield loss due to late planting is at least 15%, according to the Rotz et al. estimates.

Determination of Operation Dates

The dates when corn and soybeans can be planted under the alternative tillage systems strongly affect relative crop yields. Therefore, pre-plant tillage, planting, and post-plant nitrogen fertilizer applications were systematically scheduled according to daily soil moisture and temperature estimates for each of the 33 years for which climatic data were available. It was assumed that only one tractor and tractor operator was available for these operations, so these operations were scheduled sequentially. It was assumed that either separate equipment or custom-hired application were available for herbicide applications[4], so the daily scheduling of herbicide applications was ignored.

Criteria for determining good field days for tillage, planting, and nitrogen application were based on research by Tulu et al. (1974) and Rosenberg et al. (1982). The soil is considered to be tractable when it is not frozen and the soil moisture content is no more than a specified percentage of the soil's moisture holding capacity, or drained upper limit. In addition, the planting of corn and soybeans is not recommended when the soil temperature at planting depth is below 10° C. (50° F.). Since the CERES-MAIZE model estimates daily soil-moisture content and temperature at the center of each soil layer, it was modified to determine and report whether each day from March through June is suitable for fieldwork. Daily soil temperatures were also reported in order to determine whether each day is suitable for planting. Since the CERES-MAIZE model also had been modified to account for tillage system effects on soil moisture and soil temperature, separate good field days determinations were made for the moldboard plow system, no-till following corn, and no-till following soybeans.

Good field days determinations using the modified CERES-MAIZE model were based on soil moisture and temperature conditions in the top two soil layers, of 0-9 cm. and 9-18 cm. depth, respectively. The research by Tulu et al. (1974) and Rosenberg et al. (1982) was based on 3 relatively thin soil layers of 0-3.0 cm., 3.0-7.6 cm., and 7.6-15.2

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[4] A much smaller, utility tractor may be used to pull an herbicide sprayer. Alternatively, some farmers own self-propelled sprayers. It is also assumed that sufficient labor is available such that herbicide spraying does not compete with tillage or planting for labor resources.

cm. However, soil moisture dynamics in the CERES-MAIZE model were observed to be extremely volatile between the soil layers used by Tulu et al., and Rosenberg et al., so two relatively deep soil layers were used instead.

Soil thawing was judged to occur when the accumulation of daily average temperature in the second soil layer reached 14° C. Whenever the average daily soil temperature fell below 0° C. the accumulation was reset to zero. No heat for thawing was accumulated on days when there was snow on the ground (determined by NOAA Climatological Data). Tulu et al. and Rosenberg et al. used a similar thawing criterion of 25° F, although it was based on air temperature accumulated above 32° F.

Once soil was thawed, a day was judged to be suitable for fieldwork if it met the following criteria:

1. Precipitation on that day less than 0.75 mm. (0.03 inches).
2. For no surface residue (under the moldboard plow system): moisture in the top two soil layers no more than 95% of the drained upper limit.

   For heavy surface residue (under the no-till system):

   a. moisture in the top soil layer less than 97% of the drained upper limit, and
   b. moisture in the second soil layer less than 98% of the drained upper limit.

The less stringent moisture criteria for the no-till system are based on Rosenberg et al.'s (1982) suggestion that harvest operations can be performed with higher soil moisture contents due to the presence of crop residue. SCS state agronomist and no-till farmer, Jerry Grigar (personal communication, 1992) confirmed that no-till planting is feasible with soil moisture up to 98% of field capacity.

Good field days were then scheduled to corn planting, soybean planting, and anhydrous ammonia application according to the following criteria:

Corn Planting:

1. Pre-plant tillage on all corn acres complete (if applicable).
2. On Julian days 115-119[5], temperature of the top soil layer greater than or equal to 12° C.
3. Beginning on Julian day 120, temperature of the top soil layer greater than or equal to 10° C.

Soybean Planting:

1. Pre-plant tillage on all soybean acres complete (if applicable).
2. At least two days after the completion of corn planting.
3. Temperature of the top soil layer greater than or equal to 12° C.
4. Priority not given to anhydrous ammonia application.

Anhydrous Ammonia (NH_3) Application:

1. At least 14 days after corn was planted or 5 days after corn emergence on the same acres, whichever is later. For no-till, when corn emergence occured on Julian day 135 or later, NH_3 application was allowed 3 days after corn emergence.
2. Soybean planting complete, unless corn acres exist that have not received NH_3, have been planted at least 20 days, and had corn emergence at least 5 days earlier, in which case NH_3 application is given priority over soybean planting. Another exception is when the temperature criterion for soybean planting is not met.

The scheduling criteria for corn and soybean planting are based on standard recommendations for the northern Corn Belt (Aldrich et al.,

[5] Julian days 115-119 correspond to April 25-29, unless it is a leap year, in which case Julian days 115-119 correspond to April 24-28.

1975; Shaw, 1988, Olson and Sander, 1988; Johnson, 1987). Actually, both corn and soybean grow more vigorously when planted in soils at least 3° C. warmer than the criteria used, but waiting for warmer temperatures greatly increases the risk that wet weather will prevent planting from being completed until after optimal planting dates. A one-day gap was required between corn planting and soybean planting because the row width assumed for soybeans (15 inches) was one-half the row width assumed for corn (30 inches), and several hours would be required to attach additional planter units to the planter toolbar. The criteria for NH_3 application were set in order to give corn plants sufficient time to emerge and be clearly visible to the NH_3 applicator, but sufficiently early to assure NH_3 application within 3-4 weeks of planting and 2-3 weeks of emergence in most years. Any further delay in NH_3 application significantly reduces early corn growth and also may damage corn roots, since the NH_3 is knifed into the soil.

It was assumed that 6 days per week and 10 hours per day are available for pre-plant tillage, planting, and anhydrous ammonia application. The remaining day per week was not used due to religious observation of Sundays as a day of rest or the possibility of other agricultural activities that would require one day per week. Thus, on average, it was assumed that 8.57 hours are available for fieldwork each day. Given the machinery sizes that are presented below, this assumption resulted in requirements of approximately 9.5 good field days for disc harrowing the corn acres, 4.75 days for disc harrowing the soybean acres, 7 days for planting the corn acres, 4 days for planting the soybean acres, and 7 days for applying anhydrous ammonia to corn acres. The only two operations allowed on the same day were moldboard plowing and disc harrowing.

Pre-plant tillage for the conventional tillage system consisted of plowing with the moldboard plow, followed by two passes with a tandem disc harrow. It was assumed that all plowing must be completed before any disc harrowing is scheduled. Under scenario 1, all of the moldboard plowing is completed in the fall, leaving only the harrowing operations to complete in the spring before planting. Under scenario 2, 180 acres remain to be plowed in the spring. This requires an additional 5.7 good field days, for a total (rounded off to the nearest day) of 15 days of spring pre-plant tillage required before corn planting and an additional 5 days required before soybean planting. Under scenario 3, 330 acres remain to be plowed in the spring. This requires an additional 10.4 days, for a total (rounded off to the nearest day) of 20 days of spring pre-plant tillage required before corn planting and an additional 5 days required before soybean planting.

Production Costs

The Machinery Sets

Machinery sets (Table 4.7) were selected for the conventional and no-till systems according to two primary criteria: (1) the size of tillage and planting implements had to be sufficiently large to complete planting of 600 acres in at least 8 out of 10 years before yield penalties for late planting are incurred; and (2) the tractor had to be the smallest size capable of drawing those implements at standard operating speeds, allowing for slippage and standard reserve power recommendations (Bowers, 1987). Once tractor horsepower was determined for the implement requiring the most draft power, the size of other implements was selected to fully utilize that power, subject to two additional qualifications: (1) the size had to be available from major machinery manufacturers; and (2) eight-row equipment was selected for planters and the row cultivator. Although a 140 HP tractor is capable of pulling a twelve-row planter or row cultivator, eight-row equipment was selected because larger equipment is difficult to use on the uneven terrain frequently found in the study area. Also, the 85 HP tractor is capable of pulling an eight-row no-till planter but is not capable of pulling a larger size. The selected equipment is very consistent with the equipment selected by an heuristic machinery selection model developed for Michigan (Muhtar, 1982, Rotz et al., 1983).

Machinery Repair Costs and Trade-In Values

Machinery repair costs and trade-in values are critical parameters in a dynamic economic analysis because they may be large in comparison to the initial purchase price and other costs and because they change with time and usage. Unfortunately, these parameters also are highly variable and neither the quantity or quality of data collected for these parameters are high (Rotz and Bowers, 1991, Perry et al., 1990).

The American Society of Agricultural Engineers (ASAE) has periodically developed consensus estimates of repair costs, based on exponential functions of cumulative usage. The repair costs used in the dynamic programming model (Tables 4.8 and 4.9) are based on the latest

Table 4.7 Tillage and Planting Machinery Implements

Implement	Width	Required DBHP*	Speed (MPH)	Field Eff.**	Acres / Hr.
Moldboard Plow	7.5 feet***	93.10	4.90	0.83	3.70
Disk Harrow	20 feet	78.00	4.50	0.83	9.05
Field Cultivator	20 feet	70.40	5.50	0.83	11.07
Conv. Planter	8 rows (30")	36.96	4.50	0.69	7.53
No-Till Planter	8 rows (30")	51.84	4.50	0.67	7.31
Row Cultivator	8 rows (30")	12.80	4.00	0.80	7.76
NH3 Applicator	20 feet	69.33	4.00	0.80	7.76
Stalk Shredder	12 feet	35.20	5.50	0.85	6.80
Sprayer	30 feet	19.20	6.00	0.65	14.18

* DBHP is draw-bar horsepower. Convert to required PTO horsepower by dividing by approximately .67 on untilled soil and by .48-.56 on tilled soil, depending on soil firmness (Bowers, 1987).
** Field efficiency.
*** The moldboard plow is assumed to have 5, 18-inch bottoms.

revision of exponential function parameters proposed by Rotz and Bowers (1991). The new repair cost estimates are based on longer expected lives (measured in cumulative hours) than previous repair cost estimates. For example, the expected life of tractors has been raised from 10,000 hours (Bowers, 1987) to 12,000 hours (Rotz and Bowers, 1991).

Perry et al. (1990) recently estimated tractor remaining values from auction data. Their estimates are based on Box-Cox flexible nonlinear forms and include age, usage per year, size, condition, auction type, region, net farm income, and the real interest rate as explanatory variables. It is desirable in the dynamic programming model for the remaining value of tractors to be a function of cumulative usage alone, because the number of hours the large tractor is used per year falls by approximately 50% when the no-till system is adopted if the

Table 4.8 Repair Cost and Trade-in Values for Planters

Year*	Repair Cost Conv.	Repair Cost No-Till	Trade-in Value Conv.	Trade-in Value No-Till
0	28.24	35.80	--	--
1	92.84	117.67	8,948	10,768
2	162.62	206.13	8,053	9,691
3	235.38	298.35	7,247	8,722
4	310.29	393.29	6,523	7,850
5	386.90	490.40	5,870	7,065
6	464.92	589.30	5,283	6,358
7	544.17	689.74	4,755	5,723
8	624.48	791.53	4,280	5,150
9	705.75	894.54	3,852	4,172
10	787.87	998.64	3,466	3,755
11	870.79	1,103.73	3,120	3,379
12	954.43	1,209.75	2,808	3,041
13	1,038.74	1,316.62	2,527	2,737
14	1,123.68	1,424.28	2,274	2,463
15	1,209.21	1,532.69	2,047	2,217
16	1,295.30	1,641.80	1,842	1,995
17	1,381.91	1,751.58	1,658	1,796
18	1,469.01	1,861.98	1,492	1,616
19	1,556.59	1,972.99	1,209	1,455

* Years mark cumulative usage. A planter in year 0 is new. It is assumed that the conventional planter (Conv.) is used 80 hours per year and the no-till planter is used 82 hours per year.

Sources: Repair cost estimates are based on Rotz and Bowers (1991). Remaining values are based on Bowers (1987). List prices are based on Fuller et al. (1992).

Table 4.9 Repair Cost and Trade-in Values for Tractors

	Repair Cost		Trade-in Value	
Year	140 HP	85 HP	140 HP	85 HP
0	68.18	46.49	--	--
1	204.54	139.48	33,813	24,340
2	340.90	232.47	32,756	23,116
3	477.26	325.46	31,696	21,899
4	613.62	418.45	30,634	20,692
5	749.98	511.44	29,574	19,502
6	886.34	604.43	28,518	18,334
7	1,022.70	697.42	27,468	17,192
8	1,159.06	790.41	26,426	16,080
9	1,295.42	883.40	25,394	15,002
10	1,431.78	976.39	24,375	13,960
11	1,568.14	1,069.37	23,369	12,958
12	1,704.50	1,162.36	22,379	11,997
13	1,840.86	1,255.35	21,406	11,079
14	1,977.22	1,348.34	20,452	10,205
15	2,113.58	1,441.33	19,518	9,376
16	2,249.94	1,534.32	18,605	8,593
17	2,386.30	1,627.31	17,714	7,854
18	2,522.66	1,720.30	16,846	7,162
19	2,659.02	1,813.29	16,003	6,514
20	2,795.38	1,906.28	15,184	5,909
21	2,931.74	1,999.27	14,390	5,347
22	3,068.10	2,092.26	13,622	4,825
23	3,204.46	2,185.24	12,881	4,344
24	3,340.82	2,278.23	12,166	3,901
25	3,477.18	2,371.22	11,477	3,494
26	3,613.54	2,464.21	10,814	3,121
27	3,749.90	2,557.20	10,178	2,781
28	3,886.26	2,650.19	9,569	2,472
29	4,022.62	2,743.18	8,985	2,192
30	4,158.98	2,836.17	8,428	1,938
31	4,295.34	2,929.16	7,896	1,710
32	4,431.70	3,022.15	7,389	1,504
33	4,568.06	3,115.14	6,906	1,320
34	4,704.42	3,208.12	6,448	1,156
35	4,840.78	3,301.11	6,013	1,009
36	4,977.14	3,394.10	5,601	879
37	5,113.50	3,487.09	5,211	763
38	5,249.86	3,580.08	4,843	661
39	5,386.22	3,673.07	4,495	572
40	5,522.58	3,766.06	4,168	493

* Years mark cumulative usage in units of 400 hours per year.
A tractor in year 0 is new.

Sources: Repair cost estimates are based on Rotz and Bowers (1991). Remaining values are based on Perry (1990). List prices are for John Deere models 4455 and 2955 (NAEDA, 1992).

large tractor is kept. It is difficult to make remaining value estimates based on both age and usage per year stay consistent through this transition. Fortunately, Perry et al.'s (1990) estimates can be very closely approximated by an exponential function of cumulative hours and cumulative hours squared. In fact, the R^2 coefficient between the two functional forms is greater than 0.9997 for 20 years of 800 hours of use per year or 25 years of 400 hours of use per year (Appendix D). Remaining values for tractors in the model are based on this exponential function of cumulative hours. Remaining values for other equipment are based on Bowers (1987).

Variable Input Costs

Variable input costs considered in the model include seed, fertilizer, herbicide, insecticide, fuel and oil, grain drying, and an operating credit interest charge on these expenses. As stated in Chapter 3, the levels of these inputs are determined by the choice of tillage system. The one exception is that herbicide and fuel and oil costs for the no-till system vary according to years of experience with the no-till system. An opportunity cost charge for labor also is included, although it is assumed that no labor is hired, thus there is no interest charge for labor. The reason for including an opportunity cost charge for labor is that there usually are other farm enterprises or non-farm activities for which the allocation of additional labor would be valuable. Labor is valued at a market wage of $6.00 per hour (Nott et al., 1990). The operating credit interest charge is 6.53%, which assumes that operating credit is for 8 months at an annual rate of

9.8%, the agricultural lending rate by commercial banks in 1991 (Economic Research Service, 1992). Finally, repair costs for crop machinery other than tractors and planters are included as costs that only vary with the choice of tillage system and operating credit interest is charged on this expense. It would be more accurate to have repair costs on all machinery increase with age and/or usage. However, trying to represent this in the dynamic programming model would lead to dimensionality problems. Furthermore, repair costs for crop machinery other than tractors, planters, and harvest equipment (which does not vary significantly for different tillage systems) are relatively small.

Prices and input rates for seed, phosphorus and potassium fertilizer, and insecticide (Table 4.10) are based on representative crop budgets prepared by extension specialists at Michigan State University (Nott et al., 1990). Prices for nitrogen fertilizer are taken from the 1991 Technical Guide of the Michigan Office of the Soil Conservation Service. Input rates for recommended herbicides (Table 4.11) are based on the Michigan State extension bulletin, "1992 Weed Control Guide for Field Crops" (Kells and Renner, 1991). Herbicide prices are based on a price list compiled in February 1991 by Natalie Rector, Extension Agricultural Agent in Calhoun County, Michigan. It should be noted that three of the selected herbicides, Atrazine, Dual (Metolachlor), and Gramoxone Extra (Paraquat) are "restricted use pesticides" which require that the purchaser and applicator be certified by the Michigan Department of Agriculture. It is assumed in the model

Table 4.10 Variable Costs for MB Plow and No-Till Systems (excluding planter and tractor costs)

Variable input	Corn MB Plow	Corn No-Till	Soybeans MB Plow	Soybeans No-Till
Seed	22.50	22.50	8.40	8.40
N.Fertilizer	20.44	20.44		
P+K Fertilizer	28.40	28.40	13.19	13.19
Insecticide	7.95	7.95		
Repairs*	3.91	1.35	3.89	1.07
Harvest Costs*	16.36	16.36	13.44	13.44
Drying Costs*	18.59	18.60		
Interest	7.73	7.56	2.54	2.36
Subtotal 1	125.98	123.31	41.46	38.46
Herbicide	17.13	29.18	26.25	37.02
Fuel & Oil*	5.24	1.91	5.41	1.59
Interest	1.46	2.03	2.07	2.52
Own Labor*	6.43	3.30	6.85	2.91
Subtotal 2	30.26	36.41	40.57	44.05
Total var. costs	156.24	159.72	82.04	82.51

* See Appendix 4.3 for an explanation of these estimates. Sources for other estimates are given in the text.

Table 4.11 Herbicides Applied by Crop and Tillage System

Conventional Tillage Corn

Herbicide	Commercial Name	Amount per acre	Cost per unit	Cost per acre
Atrazine	Aatrex	1 qt. 4L	11.50	3.14
Metolachlor	Dual	1 qt.	57.00	14.25
			total cost	17.13

Conventional Tillage Soybeans

Herbicide	Commercial Name	Amount per acre	Cost per unit	Cost per acre
Metribuzin	Lexone	0.5 lb. 75%DF	24.00	12.00
Metolachlor	Dual	1 qt.	57.00	14.25
			total cost	26.25

No-Till Corn

Herbicide	Commercial Name	Amount per acre	Cost per unit	Cost per acre
Atrazine	Aatrex	1.5 qt. 4L	11.50	4.31
Metolachlor	Dual	1 qt.	57.00	14.25
Paraquat	Gramoxone	2.5 pts.	33.00	10.31
surfactant		1/6 pt.	14.52	0.30
			total cost	29.18

No-Till Soybeans

Herbicide	Commercial Name	Amount per acre	Cost per unit	Cost per acre
Metribuzin	Lexone	0.5 lb. 75%DF	24.00	12.00
Metolachlor	Dual	1 qt.	57.00	14.25
Paraquat	Gramoxone	2.5 pts.	33.00	10.31
surfactant		1/6 pt.	14.52	0.30
			total cost	37.02

that the farmer has such certification and therefore does not need to custom-hire herbicide application, which would be more costly than own-application.

Determination of Crop Prices

The corn and soybean prices used in the analysis are determined from 1955-1990 average prices for Michigan. The historical prices are adjusted for inflation by the Consumer Price Index for all items minus shelter (CPI-S) and adjusted for the effect of technology improvement. These adjustments are based on the premise that farmers view historical prices and returns in the context of what they can purchase as consumers with those prices and returns. The CPI-S index is used instead of the Consumer Price Index for all items (CPI) because it is not reasonable to assume that price inflation for urban housing (included in the CPI) reflects price inflation for rural housing. The adjustment for technology improvement reflects the fact that crop prices in 1990 dollars were much higher 25-35 years earlier than in 1990, but Michigan state average crop yields were much lower. Without the adjustment for technology improvement, the average real prices for 1955-1990 (in 1990 dollars) are $4.07 for corn and $9.55 for soybean. Compared to the current (Oct. 1991-Feb. 1992) prices of $2.30 for corn and $5.45 for soybeans, $4.07 for corn and $9.55 for soybeans probably are much higher than the prices most farmers expect in the future.

The adjustment for technology improvement consists of first estimating corn and soybean yields per acre as exponential functions of year alone, dividing the estimated crop yields for each year by the 1990 crop yields, and finally multiplying the inflation-adjusted price by this constant. The historical corn and soybean yield data were Michigan state averages. The estimated function for both corn and soybeans is:

$$\ln \text{YIELD} = a + b*\text{YEAR} + \epsilon .$$

After exponentiating, this function becomes:

$$\text{YIELD} = \exp\{a+b*\text{YEAR}\} * \exp\{\epsilon\} .$$

This functional form was chosen because it keeps the variance of the error terms approximately constant as yields increase, whereas in a linear function the variance of the error terms increases with yield. The regression estimates are presented in Appendix Table B.1 and technology trend adjustments are presented in Appendix Table B.2.

The historical average corn and soybean prices per bushel after adjustment for inflation and technology trend are $2.80 and $7.46 (in 1990 dollars), respectively (Table 4.12). These averages are reasonably close to current prices and thus might be reasonable expectations for future prices. However, the averages are strongly influenced by the extremely high prices for the period 1972-1980. Therefore, the median adjusted corn and soybean prices of $2.66 and $6.65 per bushel (in 1990 dollars) were chosen for the deterministic analysis. The median prices also have the advantage of exactly exhibiting the "rule-of-thumb" price ratio of 2.5 between corn and soybeans in the Corn Belt.

For the stochastic analysis, the adjusted corn and soybean prices were sorted by size and divided into three groups of low, medium, and high prices, with 12 observations each. The average corn prices within

Table 4.12 Adjusted Corn and Soybean Prices*, ($/bu.), 1955-90.

				CPI - shelter Adjusted prices		CPI - shelter & tech. adjusted	
Year	Corn	Soybean	CPI - shelter	Corn	Soybean	Corn	Soybean
1955	1.25	2.20	28.4	5.64	9.93	2.73	6.05
1956	1.23	2.14	28.8	5.48	9.53	2.71	5.88
1957	1.12	2.06	29.7	4.83	8.89	2.44	5.57
1958	1.09	1.94	30.6	4.57	8.13	2.35	5.16
1959	1.04	1.97	30.8	4.33	8.20	2.28	5.28
1960	0.99	2.08	31.3	4.05	8.52	2.18	5.57
1961	0.99	2.23	31.7	4.00	9.02	2.20	5.98
1962	1.05	2.33	32.0	4.21	9.33	2.36	6.28
1963	1.08	2.50	32.4	4.27	9.89	2.44	6.75
1964	1.15	2.56	32.8	4.49	10.01	2.62	6.92
1965	1.15	2.56	33.3	4.43	9.86	2.64	6.91
1966	1.22	2.72	34.3	4.56	10.17	2.77	7.23
1967	0.97	2.47	35.2	3.53	9.00	2.19	6.49
1968	1.03	2.39	36.7	3.60	8.35	2.28	6.11
1969	1.14	2.33	38.4	3.81	7.78	2.46	5.78
1970	1.32	2.84	40.3	4.20	9.03	2.78	6.80
1971	1.03	3.05	42.0	3.14	9.31	2.12	7.11
1972	1.49	4.60	43.3	4.41	13.62	3.04	10.55
1973	2.52	5.73	46.2	6.99	15.90	4.92	12.50
1974	2.91	6.28	51.4	7.26	15.66	5.21	12.48
1975	2.35	4.78	56.0	5.38	10.94	3.94	8.85
1976	2.04	7.22	59.3	4.41	15.61	3.30	12.80
1977	1.92	5.54	63.1	3.90	11.26	2.98	9.36
1978	2.22	6.81	67.4	4.22	12.95	3.29	10.93
1979	2.48	6.13	74.2	4.28	10.59	3.41	9.06
1980	3.07	7.49	82.9	4.75	11.58	3.86	10.05
1981	2.35	6.04	91.0	3.31	8.51	2.75	7.49
1982	2.48	5.46	96.2	3.30	7.28	2.80	6.50
1983	3.20	7.82	99.8	4.11	10.05	3.56	9.10
1984	2.56	5.79	103.9	3.16	7.14	2.79	6.56
1985	2.14	4.93	107.0	2.56	5.91	2.31	5.50
1986	1.43	4.67	108.0	1.70	5.54	1.56	5.24
1987	1.97	5.62	111.6	2.26	6.46	2.13	6.19
1988	2.53	7.28	115.9	2.80	8.05	2.68	7.83
1989	2.28	5.60	121.6	2.40	5.90	2.35	5.82
1990	2.23	5.75	128.2	2.23	5.75	2.23	5.75
Mean				4.07	9.55	2.80	7.46

* Adjusted for inflation and technology trend, as explained in the text and Appendix B. All adjusted prices are in 1990 dollars.

each of the three groups are $2.18, $2.62, and $3.59 per bushel (in 1990 dollars). The average soybean prices within each of the three groups are $5.63, $6.65,and $10.08 per bushel. The averages for the low corn and soybean price groups are very near the current prices of $2.30 for corn and $5.45 for soybeans, which facilitates interpretation of results for the stochastic analysis. The close proximity of the averages for the medium corn and soybean price groups to the median prices used in the deterministic analysis also facilitates interpretation of the stochastic results.

Computer Implementation of the Dynamic Programming Model

The dynamic programming replacement model is written in Microsoft FORTRAN, Ver. 5.1 (Microsoft, 1991) and solved on a microcomputer with an 80486 processor. The program for the deterministic model (Appendix G) consists of four main parts: (1) a section to set array dimensions, define common blocks of shared variables, read a file of input data, and set initial values; (2) a section that counts backwards through time and calls the subroutines that determine optimal policies and value functions for all of the state variables for each year; (3) the subroutines for each ownership state that determine the optimal policies and calculate the value functions; and (4) a section that reconstructs optimal policies beginning in year one and reports the optimal decisions made in each year of the planning horizon. The program for the stochastic model (Appendix H) omits the fourth section because all optimal decisions are dependent on the stochastic state variable outcomes at that stage, so only the initial decision is very meaningful.

Furthermore, the extra dimensions required by the stochastic state variables preclude storing optimal policy values throughout the time horizon for all levels of state variables.

Solution times on the 80486 microcomputer range from 40 to 100 seconds for the deterministic dynamic programming model and from 11 to 19 hours for the stochastic dynamic programming model. Solution times are approximately 30% less when assuming a relative risk-aversion coefficient of 0.5 for the stochastic model than when assuming a relative risk-aversion coefficient of 1.0. This indicates that the Microsoft FORTRAN algorithm for calculating square roots is more efficient than its algorithm for calculating natural logarithms.

The programs for both the deterministic and stochastic models will write optimal policies to the output file for all planter and tractor ages up to the initial ages specified in the input file. This allows optimal policies to be determined for a wide range of initial planter and tractor ages in a single run. However, selecting high initial planter and tractor ages slightly increases solution times and greatly increases the size of the output file. The programs for both models also write differences between the value function for the optimal policy and the value functions for alternative policies to the output file. This allows one to see how close other policy choices are to being selected as optimal.

Chapter 5

RESULTS FOR OPERATION DATES, CROP YIELDS AND NET REVENUES

Since the results for the dynamic programming replacement model depend largely on crop yields for the two tillage systems, the crop yields obtained through the crop simulation models are presented first. The crop yields, themselves depend on the determination of good field days and the scheduling of planting and fertilizer application operations for the 33 years considered. This chapter therefore presents the good field day results, operation dates, and crop yields for the 33 years, the alternative tillage systems, and the different scenarios concerning the proportion of plowing completed in the fall.

This chapter goes on to present the two most common forms of economic analysis for conservation tillage, namely comparative budget analysis and stochastic dominance analysis. It will be interesting to compare the results of these static economic analyses with the results of dynamic economic analyses that follow in Chapter 6.

Results are presented from the perspective of the farm manager who makes machinery and technology decisions. As explained in Chapter 4, the determination of which days are suitable for fieldwork (good field days) is important because it affects planting and fertilizer application dates, which then affect crop yields for the alternative tillage systems. Criteria used to determine which days are suitable for fieldwork are presented in Chapter 4. Good field days results are presented for 3 levels of fall plowing completion because a low level of fall plowing completion may delay planting and reduce crop yields under the conventional tillage system. Crop yields are presented as averages over all fields and planting dates for each year because the individual fields utilize the same pool of machinery and labor resources. The individual fields also contribute to the same pool of revenue. Net revenues are presented at the farm level because machinery decisions and payments are made at the farm level.

Good Field Days Results

The number of days determined to be suitable for fieldwork is usually but not always sufficient to complete pre-plant tillage operations before optimal dates for corn planting, based on the 33 years of climatic data and the characteristics of the Oshtemo sandy loam. Under conventional tillage, good field days are rare before mid-March (Julian day 74), but increase rapidly in frequency until about April 8 (Julian day 98), when the frequency levels off between 60% and 70% (Figure 5.1). On average, 10 days are suitable for fieldwork before April 9 (Julian day 99), 15 days are suitable for fieldwork by April 17 (Julian day 107), 20 days are suitable for fieldwork by April 25 (Julian day 115), and 25 days are suitable for fieldwork by May 3 (Julian day 123). Thus, when 70% or more of the 600 acres are plowed in the fall, corn planting can begin in the average year on the second day allowed (Julian day 116)[1]. Even when only 45% of the 600 acres are plowed in the fall, corn planting can begin in the average year on Julian day 124,

[1] It was determined in Chapter 4 that under the 70% fall plowing scenario, 15 days of pre-plant tillage must be scheduled in the spring before corn planting.

Figure 5.1

Good Field Days Probability, MB Plow System, on an Oshtemo Sandy Loam in Michigan, 1953-78, 1984-90.

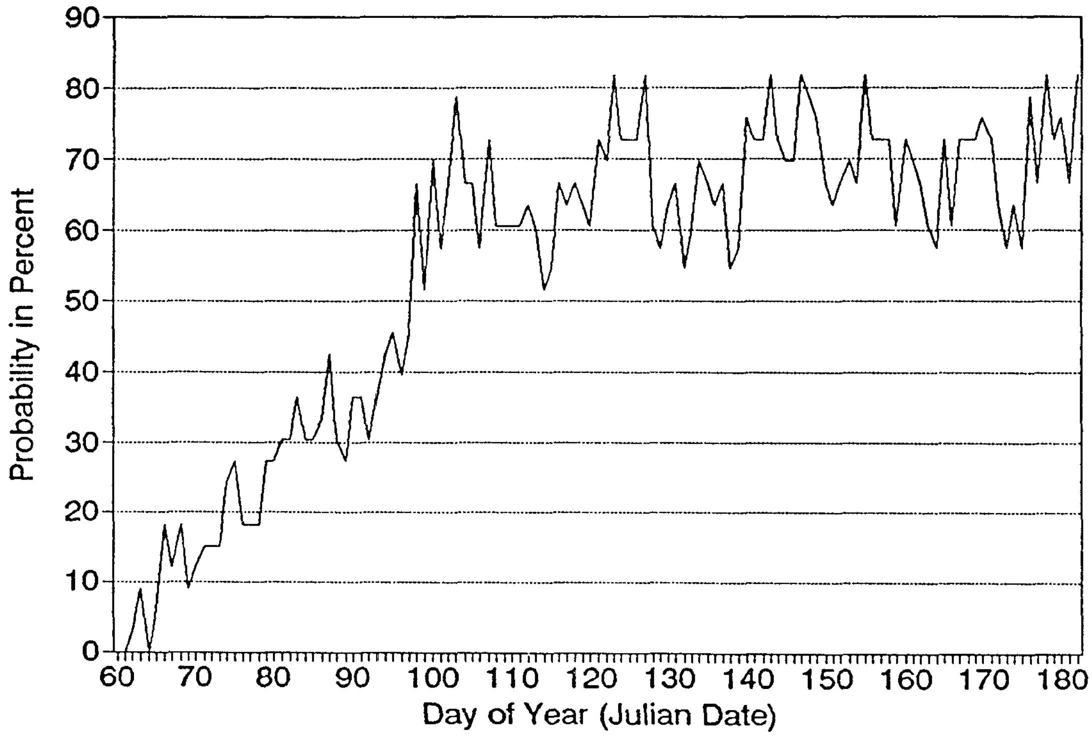
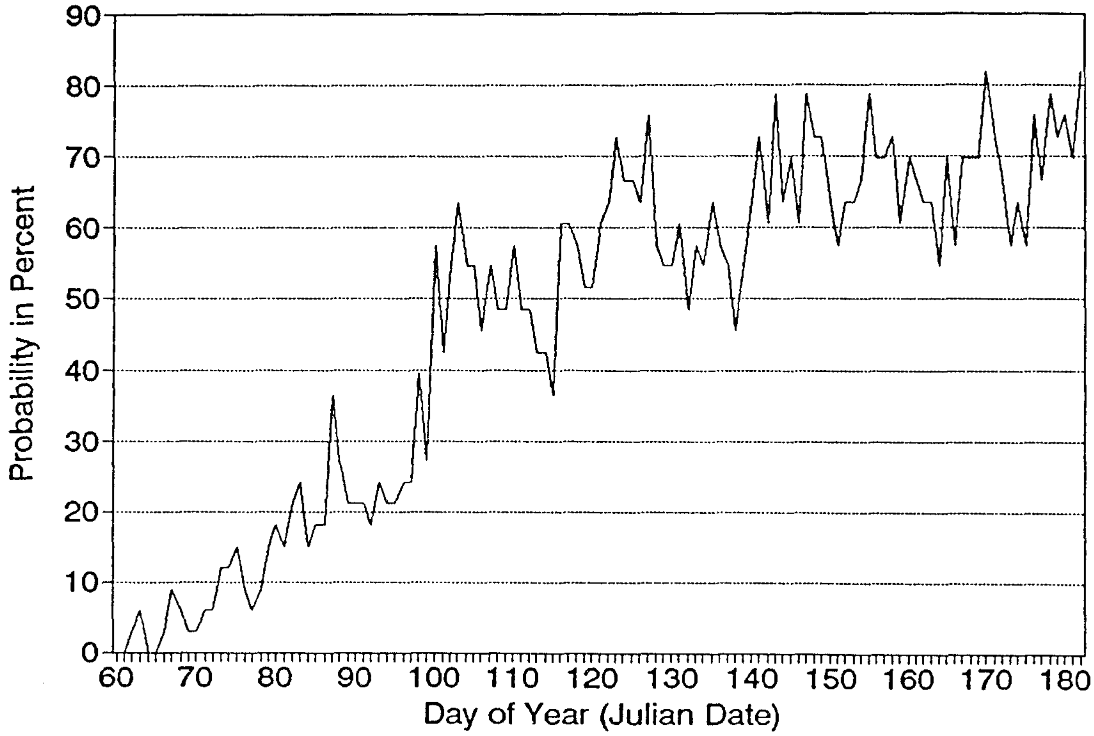


Figure 5.2

Good Field Days Probability, No-Till System, on an Oshtemo Sandy Loam in Michigan, 1953-78, 1984-90.



which still leaves 7 days for corn planting before any yield penalty for late planting is likely[2].

Of course, there is variation around the average numbers of good field days (Table 5.1). In 19 out of 33 years (57.6%) there are only 20 good field days before May 1 (Julian day 121). In 2 out of 33 years (6.1%) there are only 15 good field days before May 1. There is one year out of 33 (3.0%) when there are only 20 good field days before May 11, which means that most corn fields in that year would be planted after the period that is considered optimal by Rotz et al. (1983).

Although pre-plant tillage is not needed under the no-till system, it is instructive to compare the average number of estimated good field days with surface corn residue to the number of estimated good field days without surface residue (compare Figure 5.2 with Figure 5.1). On

Table 5.1 Total Good Field Days by Specified Dates, MB Plow System

Date	No. of Years out of 33	No. of Good Field Days less than or equal to:
April 25	9	15
April 25	19	20
April 25	25	25
April 30	2	15
April 30	12	20
April 30	24	25
May 10	0	15
May 10	1	20
May 10	9	25

[2] It was determined in Chapter 4 that under the 45% fall plowing scenario, 20 days of pre-plant tillage must be scheduled in the spring before corn planting.

the average with surface corn residue, 10 days are suitable for fieldwork before April 17 (Julian day 107), 15 days are suitable for fieldwork by April 27 (Julian day 117), 20 days are suitable for fieldwork by May 6 (Julian day 126), and 25 days are suitable for fieldwork by May 14 (Julian day 134). The frequency of good field days also is less for the no-till system during the peak planting periods for corn and soybeans. In the period of May 1-20 (Julian dates 121-140), 67% of the days are suitable for fieldwork under conventional tillage, versus 60% under the no-till system. The difference in days suitable for planting between the alternative tillage systems is even greater than this, due to the minimum temperature criteria for planting and reduced soil temperatures for the no-till system (Chapter 4). The difference in good field days between the alternative tillage systems narrows after May 20. In the period of May 21-June 31 (Julian dates 141-181), 70% of the days are suitable for fieldwork under conventional tillage, versus 68% under the no-till system.

Scheduling of Crop Operations

Under all three scenarios for the proportion of plowing completed in the fall, the average date of corn planting for the 33 years with conventional tillage is very timely on the Oshtemo sandy loam (Table 5.2). When 100% of plowing is completed in the fall, the average corn planting date is May 3 (Julian day 123). When the proportion of fall plowing is 70%, the average corn planting date is May 4 (Julian day 124), and when the proportion of fall plowing is 45%, the average corn planting date is May 6 (Julian day 126). Soybeans also can be planted in a timely manner under all three scenarios for fall plowing completion (Table 5.2). However, the standard deviation of planting dates is large, especially for soybeans, and increases as the proportion of plowing completed in the fall decreases.

Table 5.2 Average Operation Dates*, by Tillage System

	Corn Planting	Soybean Planting	NH_3 Application
MB Plow System:			
100% Fall Plowing	122.9	134.0	142.3
	(5.0)	(6.8)	(5.6)
70% Fall Plowing	123.6	136.0	143.7
	(5.3)	(7.5)	(5.8)
45% Fall Plowing	125.9	140.7	146.2
	(6.6)	(10.7)	(7.8)
No-Till System	123.6	135.2	142.5
	(5.6)	(6.4)	(7.7)

* Values in parentheses are standard deviations over 33 years. The dates are expressed as Julian dates. All of the days in this table are May dates, in which case the day within May is the Julian date minus 120 (minus 121 in leap years). The values in parentheses are standard deviations over 33 years. All of the operation dates are presented in Appendix F.

Average operation dates for the no-till system are approximately the same as for moldboard plowing with 70% of plowing completed in the fall. Therefore, the no-till system does not lead to earlier or later operation dates than the conventional tillage system on the Oshtemo sandy loam in an average year.

Crop Yields

The average crop yield estimates for corn and soybeans do not differ much between the two alternative tillage systems (Table 5.3). The mean estimated corn yield for the conventional tillage system with 70% fall plowing is 110.0 bushels per acre, whereas the mean estimated corn yield for the no-till system is 110.3 bushels per acre. However, the coefficients of variation for the estimated corn yields are 39% and 38%, respectively for these two cases. A difference of 1.6 bushels per acre would be required to say that the mean corn yields for these two cases are significantly different with probability of Type I error (α) set at 20%[3]. The mean estimated soybean yield for the conventional tillage system with 70% fall plowing is 34.4 bushels per acre, whereas the mean estimated soybean yield for the no-till system is 35.6 bushels per acre. The respective coefficients of variation are 35% and 34%. The difference between the means of the estimated soybean yields for 70% fall plowing and for no-till is statistically significant, (α=1%)[4].

The variation in crop yields clearly is much greater between years than between the tillage systems, (Table 5.3, Figures 5.3 and 5.4). However, in some years there is a clear difference in corn yields

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[3] Determined by the confidence interval for paired differences (Mendenhall et al, 1986). Testing the paired differences is appropriate because each pair of estimated yields is influenced by the same weather conditions and the probability distribution for the paired differences is approximately normal. The Chi-square statistic for the hypothesis that the distribution is normal is 2.1, with five degrees of freedom.

[4] The t-statistic for paired differences (Mendenhall et al, 1986) in this case equals 4.1. The Chi-square statistic for the hypothesis that the distribution of differences between the means is normal equals 3.7, with 5 degrees of freedom.

Table 5.3 Mean Estimated Crop Yields (BU/A) for 70% Fall Plowing and No-Till, with July and August rainfall (inches).

	70% Fall MB Plow		No-Till		Rainfall	
Year	corn	soybean	corn	soybean	July	August
1953	112.81	27.63	114.38	28.88	2.39	3.22
1954	63.33	16.58	68.09	19.03	2.26	1.73
1955	103.82	33.55	106.15	35.88	3.59	3.29
1956	117.84	48.00	112.83	49.65	2.54	5.20
1957	142.07	29.70	131.69	29.88	8.44	1.42
1958	154.23	43.45	160.39	44.28	4.58	3.49
1959	134.43	57.38	131.94	59.75	5.59	4.54
1960	99.81	36.43	101.54	36.33	1.97	3.83
1961	101.49	47.90	105.11	49.40	2.71	3.97
1962	62.26	21.28	61.75	24.93	2.41	1.85
1963	128.13	42.25	134.61	43.38	2.91	3.05
1964	103.33	28.95	107.43	32.08	2.23	4.04
1965	49.48	23.13	51.17	21.08	0.79	3.73
1966	84.69	20.95	81.29	22.43	2.33	3.28
1967	48.82	19.78	49.21	20.33	1.46	2.98
1968	138.13	30.00	128.57	29.98	2.34	2.23
1969	162.91	32.70	162.86	37.93	6.65	0.45
1970	165.41	38.85	159.36	42.08	6.98	1.58
1971	76.29	17.43	79.91	19.83	2.89	1.70
1972	97.10	39.03	99.35	40.78	2.19	3.11
1973	55.84	17.03	57.74	17.85	1.45	1.84
1974	55.26	25.45	54.03	22.00	1.40	3.52
1975	106.63	38.08	111.51	38.35	2.18	7.62
1976	62.86	15.98	58.24	17.98	4.44	0.49
1977	139.64	40.70	149.98	41.15	3.41	2.06
1978	82.59	25.90	86.11	24.53	1.51	2.81
1984	69.86	28.73	81.63	29.35	3.34	1.68
1985	174.96	42.55	167.00	43.70	5.20	3.80
1986	213.96	58.95	201.54	59.70	6.50	4.00
1987	102.68	47.95	106.16	50.58	2.70	5.80
1988	77.61	50.83	76.91	52.73	4.17	4.94
1989	161.96	45.73	162.16	46.85	2.30	4.00
1990	178.46	41.45	177.78	40.95	2.00	3.20
Mean	109.96	34.37	110.25	35.56	3.27	3.17
C.V.	39.1%	34.9%	37.5%	34.3%	55.4%	33.6%

Figure 5.3

Estimated Corn Yields, MB Plow and No-Till, on an Oshtemo Sandy Loam in Michigan, 1953-78, 1984-90.

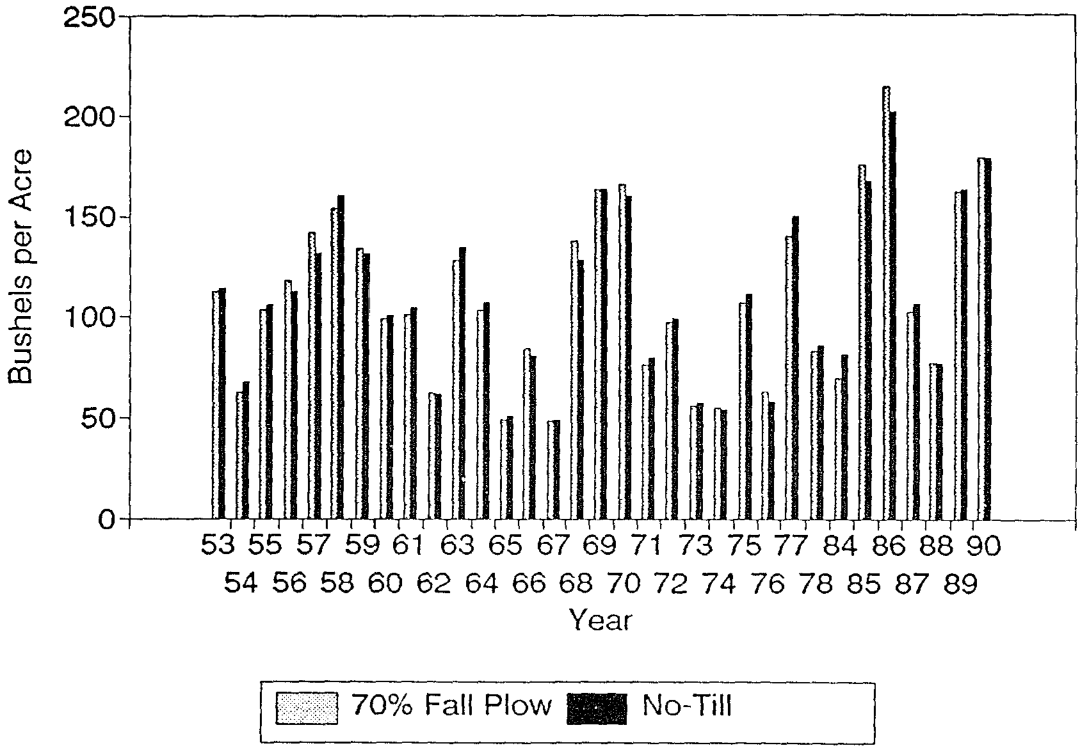
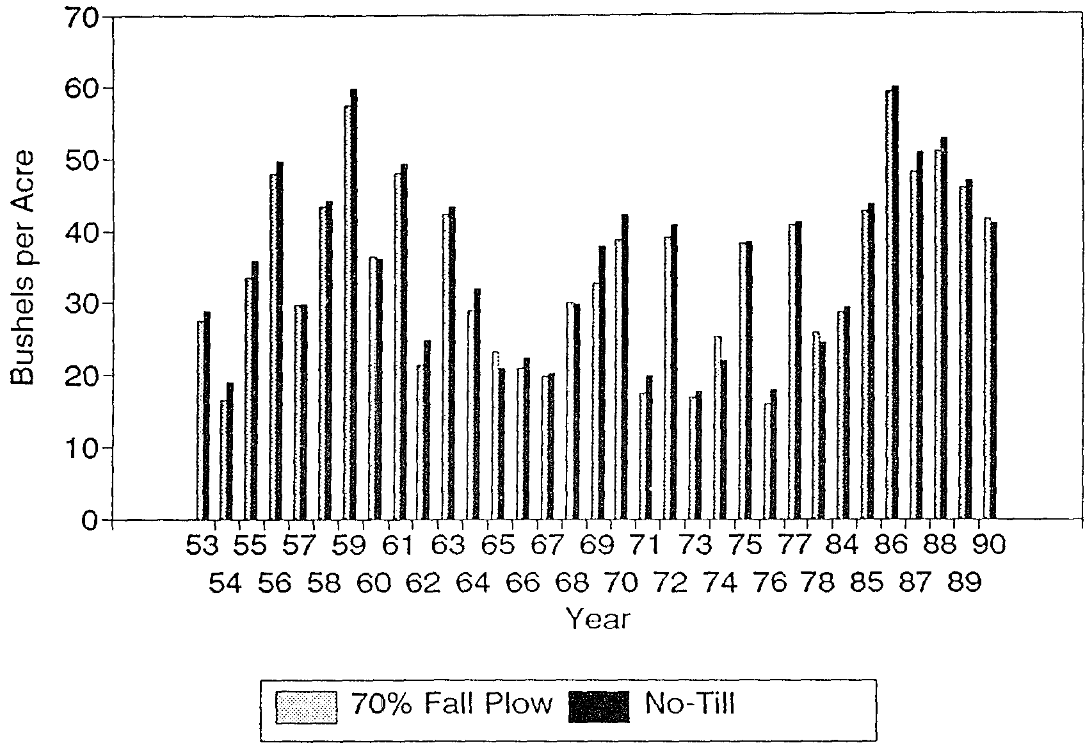


Figure 5.4

Estimated Soybean Yields, MB Plow and No-Till, on an Oshtemo Sandy Loam in Michigan, 1953-78, 1984-90.



(Figure 5.5) and soybean yields (Figure 5.6) between the two tillage systems. In 10 out of 33 years (30%) there is at least a 5 bushel per acre difference in corn yields and in 12 out of 33 years (36%) there is at least a 2 bushel per acre difference in soybean yields.

The average corn and soybean yield estimates vary very little between the three levels of fall plowing completion under conventional tillage. The average corn yield in bushels per acre is 110.1 for 100% fall plowing, 109.7 for 70% fall plowing, and 109.3 for 45% fall plowing (Table 5.4). The average soybean yield actually increases slightly as spring operations are delayed due to the need to complete plowing in the spring. The average soybean yield in bushels per acre increases from 34.1 for 100% fall plowing to 34.3 for 70% fall plowing, to 34.7 for 45% fall plowing (Table 5.4).

Mean estimated corn yields for 100% fall plowing and 45% fall plowing are not statistically different from mean estimated corn and yields for the no-till system. A difference of 1.4 bushels per acre would be required to say that the mean corn yields for 100% fall plowing and no-till are significantly different (α=20%), compared to the estimated difference of 0.2 bushels[5]. A difference of 2.6 bushels per acre would be required to say that mean corn yields for 45% fall plowing and no-till are significantly different (α=20%), compared to the estimated difference of 1.0 bushel[6].

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[5] The Chi-square statistic for the hypothesis of a normal distribution equals 6.4.

[6] However, the Chi-square statistic for the distribution of differences between the mean yields for 45% fall plowing and no-till equals 11.2, which leads to rejecting the hypothesis of a normal distribution (α=.05).

Figure 5.5

Estimated Corn Yields, No-Till minus MB Plow, on an Oshtemo Sandy Loam in Michigan, 1953-78, 1984-90.

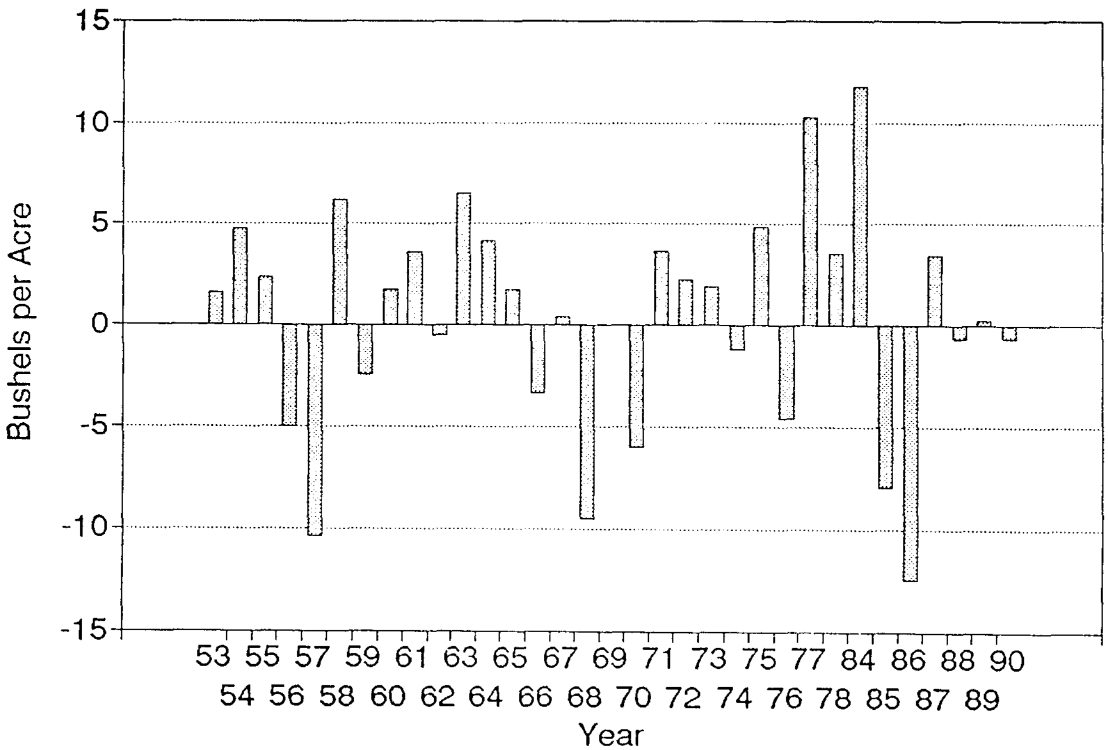

Figure 5.6

Estimated Soybean Yields, No-Till minus MB Plow, on an Oshtemo Sandy Loam in Michigan, 1953-78, 1984-90.

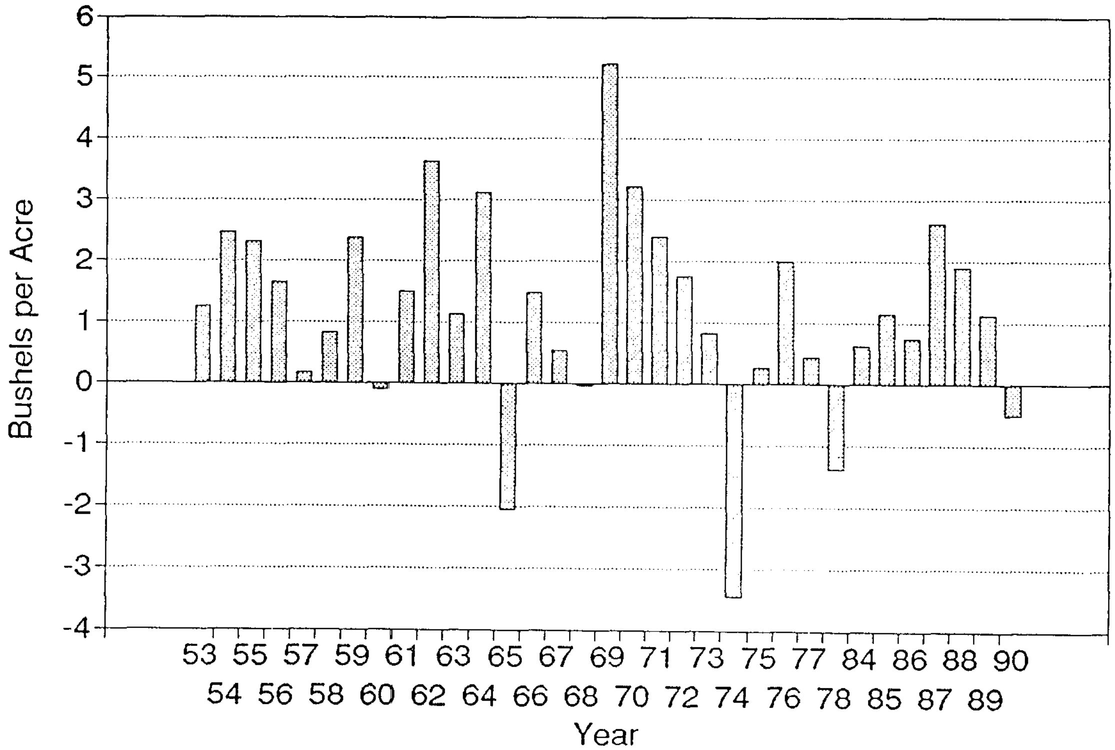

Table 5.4 Average Corn and Soybean Yields (BU/A) for 100%, 70%, and 45% completion of plowing in the fall.

Year	100% Fall Plowing Corn	100% Fall Plowing Soybean	70% Fall Plowing Corn	70% Fall Plowing Soybean	45% Fall Plowing Corn	45% Fall Plowing Soybean
1953	112.81	27.63	112.81	27.63	112.81	27.60
1954	69.03	17.33	63.33	16.58	60.90	16.20
1955	103.82	33.55	103.82	33.55	103.76	33.43
1956	117.84	48.00	117.84	48.00	109.27	48.33
1957	142.07	29.70	142.07	29.70	142.07	25.08
1958	154.23	43.45	154.23	43.45	154.23	43.45
1959	134.43	57.38	134.43	57.38	134.30	59.53
1960	100.37	36.75	99.81	36.43	81.45	24.98
1961	101.49	47.90	101.49	47.90	101.49	47.90
1962	62.26	21.28	62.26	21.28	62.26	21.28
1963	128.13	42.25	128.13	42.25	128.13	42.25
1964	103.33	28.95	103.33	28.95	103.33	28.95
1965	47.98	21.38	49.48	23.13	43.69	29.95
1966	84.69	20.95	84.69	20.95	84.70	20.95
1967	48.79	19.70	48.82	19.78	49.24	20.60
1968	138.13	30.00	138.13	30.00	138.13	30.00
1969	164.06	38.10	162.91	32.70	161.95	27.65
1970	162.90	41.13	165.41	38.85	173.88	37.18
1971	76.31	17.43	76.29	17.43	76.29	17.43
1972	97.08	39.03	97.10	39.03	98.18	43.83
1973	55.84	17.03	55.84	17.03	55.84	17.03
1974	54.16	21.58	55.26	25.45	57.90	27.58
1975	106.87	35.08	106.63	38.08	106.87	45.08
1976	62.86	15.98	62.86	15.98	62.86	15.98
1977	139.64	40.70	139.64	40.70	139.74	39.78
1978	82.51	20.43	82.59	25.90	84.95	29.28
1984	70.01	28.30	69.86	28.73	74.74	27.60
1985	174.96	42.55	174.96	42.55	174.96	42.55
1986	213.96	58.95	213.96	58.95	213.96	58.95
1987	102.68	47.95	102.68	47.95	102.68	47.95
1988	77.61	50.83	77.61	50.83	77.50	52.10
1989	161.96	45.50	161.96	45.73	159.09	45.73
1990	178.79	39.50	178.46	41.45	174.21	47.78
Mean	110.05	34.13	109.96	34.37	109.25	34.66
C.V.	38.8%	35.9%	39.1%	34.9%	39.7%	36.1%

Mean estimated soybean yields for 100% fall plowing are significantly different than the mean estimated soybean yields for no-till (α=1%)[7]. However, the mean estimated soybean yields for 45% fall plowing are not significantly different from the estimated no-till yields. A difference of 1.9 bushels per acre would be required to say that mean soybean yields for 45% fall plowing and no-till are significantly different (α=20%), but the difference in the estimated means is only 1.4 bushels.[8].

The level of estimated crop yield variation is not unusual for a sandy soil. Furthermore, all of the unusually high and low crop yields can be readily explained. The July and August precipitation amounts (Table 5.3) explain much of the variation in crop yields. July is when both corn and soybean plants usually start their reproductive development and are most sensitive to moisture stress. Corn and soybean plants usually are filling their grain or seed with biomass during August, so moisture stress in August directly reduces corn grain and soybean seed yield. The modified CERES-MAIZE and SOYGRO models provide additional information concerning the magnitude of stresses and the timing of those stresses with respect to phenological stage.

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[7] The t-statistic for the paired differences equals 7.3 and the Chi-square statistic for testing whether the distribution of differences is normal equals 3.3 in this case.

[8] The Chi-square statistic for the distribution of differences between mean yields for 45% fall plowing and no-till equals 18.6, which leads to rejecting the hypothesis of a normal distribution (α=.05). However, the observed differences mostly depart from a normal distribution by having an extremely high density in the interval between zero and 0.5 standard deviations above the mean.

The average corn yield exceeded 150 bushels per acre in 7 of the 33 years, with the average corn yields exceeding 200 bushels per acre in 1986. In 1986, 17.5 inches of rainfall in May-September were so well distributed that the CERES-MAIZE model reported zero moisture stress in every phenological stage for both conventional tillage and no-till. Five of the 7 years with corn yields in excess of 150 bushels per acre had July rainfall in excess of 4.5 inches. The other two years with corn yields in excess of 150 bushels per acre (1989 and 1990) had May and June rainfall in excess of 4 inches and rapid phenological development, so corn plants were able to complete the silking stage before moisture became limiting.

The average corn yield was less than 80 bushels per acre in 9 of the 33 years. In 5 of these 9 years the July or August rainfall was less than 1.5 inches, and in 8 of these 9 years either the July or August rainfall was less than 2.1 inches. The other year with average corn yield less than 80 bushels per acre was 1988, in which only 2.6 inches of rain fell from May 1 to July 15. In both of the years with the average corn yield less than 50 bushels per acre, the July rainfall was less than 1.5 inches. In each of the two years with corn yield less than 50 bushels per acre, corn plants also matured early due to low September temperatures.

In 7 of the 9 years with corn yields less than 80 bushels per acre, the average soybean yields were less than 25 bushels per acre. Again, low rainfall in July or August was largely responsible for the low soybean yields. The one year in which soybean yielded around 50 bushels per acre, but corn yielded less than 80 bushels per acre, was

1988, in which soybeans were little affected by the drought in May through mid-July and benefitted greatly from the abundant rainfall after mid-July.

In the three years with soybean yields greater than 50 bushels per acre (1959, 1986, and 1988), July and August rainfall were at least 4 inches. For 1986, the SOYGRO model reported only one growth stage with drought stress above 0.1 on a 0-1 scale. For 1959 and 1988, the maximum drought stress levels were similar to those of other years, but occurred at a much earlier growth stage (first pod) than in most other years.

Comparative Budget Results

After multiplying average estimated yields by historical median prices and subtracting variable costs[9] for each tillage system, the most striking result is the near equality of revenues net of variable costs for the alternative tillage systems and levels of fall plowing completion. The highest revenues net of variable costs, $84,241, are obtained for the no-till system (Table 5.5). However, the revenues net of variable costs for the conventional tillage system with 70% of plowing completed in the fall are only $416 less, a difference of only 0.5%, and the revenues net of variable costs for the other two levels of fall plowing completion are within $783 of those for the no-till system, a difference of only 0.9%. Gross revenues are slightly higher for the no-till system than for conventional tillage under any level of fall

[9] The variable costs considered here exclude repair costs for the tractor and planter because these repair costs varied with accumulated usage.

plowing completion, but variable costs also are slightly higher for the no-till system (Table 4.10), resulting in little or no net advantage.

Under the current prices of $2.30 per bushel of corn and $5.45 per bushel of soybeans, the no-till system provides revenues net of variable costs that are only $88 (0.15%) more than those for 70% fall plowing.

Table 5.5 Revenues Net of Variable Costs*, MB Plow and No-Till

Tillage system and percent fall plowing completion	Corn Net Revenue ($/acre)	Soybean Net Revenue ($/acre)	600 Acre Net Revenue ($)	Average Net Revenue, C-C-S Rotation ($/acre)
With $2.66/bu. corn and $6.65/bu. soybeans				
100% Fall Plow	136.54	144.89	83,593	139.32
70% Fall Plow	136.31	146.50	83,825	139.71
45% Fall Plow	134.42	148.45	83,459	139.10
No-Till System	133.63	153.95	84,241	140.40
With $2.30/bu. corn and $5.45/bu. soybeans				
100% Fall Plow	96.92	103.93	59,555	99.26
70% Fall Plow	96.73	105.26	59,742	99.57
45% Fall Plow	95.09	106.85	59,407	99.01
No-Till System	93.94	111.28	59,830	99.72

* Based on mean yields estimated for 33 years on an Oshtemo soil, as presented in Tables 5.3 and 5.4. Variable costs are presented in Table 4.10, and exclude tractor and planter repair costs.

Since the no-till system provides slightly higher yields than conventional tillage but has higher variable costs, any reduction in crop prices hurts the relative profitability of the no-till system.

Furthermore, since the no-till system provides a greater yield advantage over conventional tillage for soybeans than for corn, the low ratio between current soybean and corn prices of 2.37 also hurts the relative profitability of the no-till system.

If the tillage implements not used under the no-till system were sold, the reduction in fixed costs for shelter, insurance, and taxes according to Hunt (1983)[10] would be $733. Hence, even ignoring depreciation which is by far the largest component of fixed costs[11], the relative profitability of the no-till system increases greatly when possible reductions of fixed costs are considered. Revenues net of variable costs also would be significantly higher for the no-till system than for the conventional tillage system under any level of fall plowing completion if average repair costs for the planter and tractor are considered and the 85 HP tractor is used for the no-till system. Almost all previous analyses of the relative profitability of no-till systems (e.g. Smith and Hallam, Klemme, Williams) have made both of these assumptions and concluded that the no-till system is more profitable than conventional tillage in the long run.

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[10] Hunt (1983) states that costs for shelter, insurance, and taxes are very nearly fixed, and can be estimated as 2.5% of the purchase price. If the purchase price is assumed to be 85% of the list price, 2.5% of the purchase price for the moldboard plow, tandem disc, field cultivator, and row cultivator is $733.

[11] Under any depreciation method, the annual depreciation cost will be at least 8% of list price according to estimates by Bowers (1987). This assumes that tillage equipment is kept 10 years and sold after 10 years for 20% of its list price. Use of any declining-balance method of depreciation and any positive discount rate will increase the annual depreciation cost above 8%.

Variation in Net Revenue and Stochastic Dominance Results

Although there are only small differences in mean net revenues between the alternative tillage systems, there often are very sizeable differences in the annual results for revenue net of variable costs (Figures 5.7-5.9). Comparing revenues net of variable costs for no-till and 100% fall plowing, there are 2 years in which the no-till system provides at least $10,000 more, but 3 years in which the no-till system provides at least $10,000 less than 100% fall plowing (Figure 5.7). The number of years in which the difference in revenues net of variable costs for no-till and 70% fall plowing exceeds plus and minus $10,000 is the same (Figure 5.8). What is more interesting about the comparison of revenues net of variable costs for no-till and 70% fall plowing is the result that no-till provides at least $5,000 more in 9 years but at least $5,000 less than 70% fall plowing in five years. The variability of relative revenues net of variable costs is still greater when comparing the no-till system with 45% fall plowing (Figure 5.9). In 8 of 33 years no-till provides revenues net of variable costs that are at least $10,000 more or $10,000 less than 45% fall plowing. In 20 of 33 years, no-till provides revenues net of variable costs that are at least $5,000 more or $5,000 less than 45% fall plowing.

Revenues net of variable costs clearly do not exhibit first-degree stochastic dominance (FSD) for the no-till system over conventional tillage with any of the three levels of fall plowing completion because the cumulative distribution functions (CDF's) cross (Figures 5.10-5.12).

Figure 5.7

Revenue Net of Variable Costs, No-Till minus 100% Fall Plowed, on an Oshtemo Sandy Loam in Michigan, 1953-78, 1984-90.

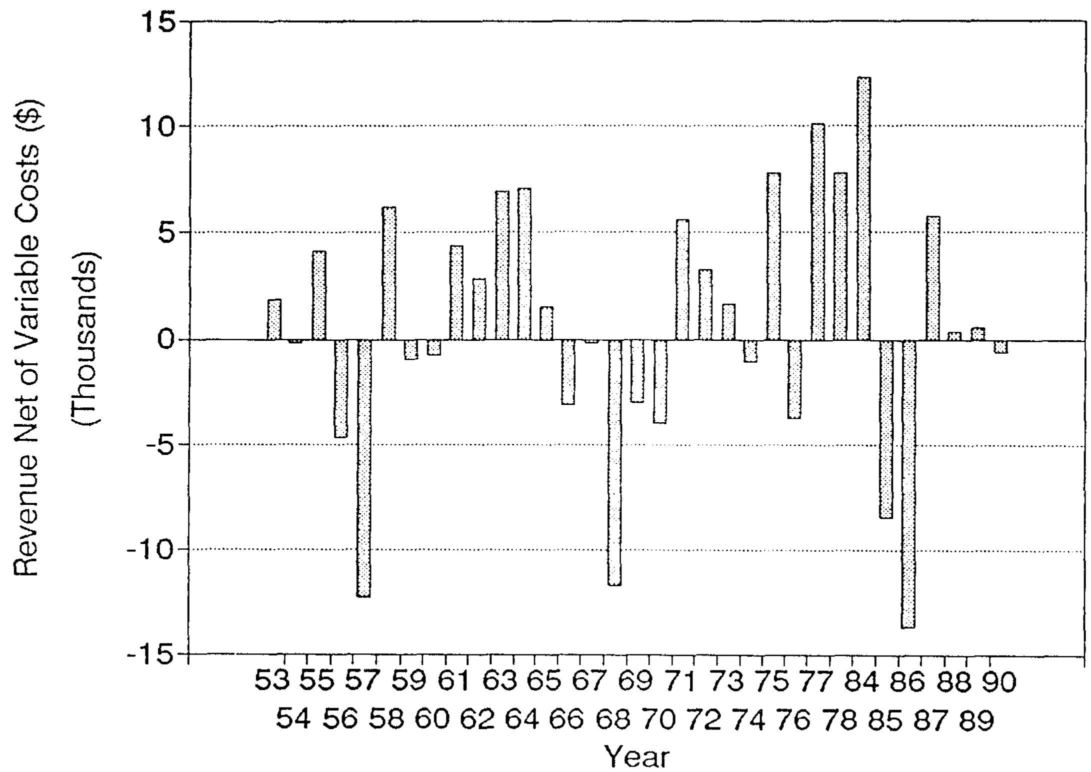


Figure 5.8

Revenue Net of Variable Costs, No-Till minus 70% Fall Plowed, on an Oshtemo Sandy Loam in Michigan, 1953-78, 1984-90.

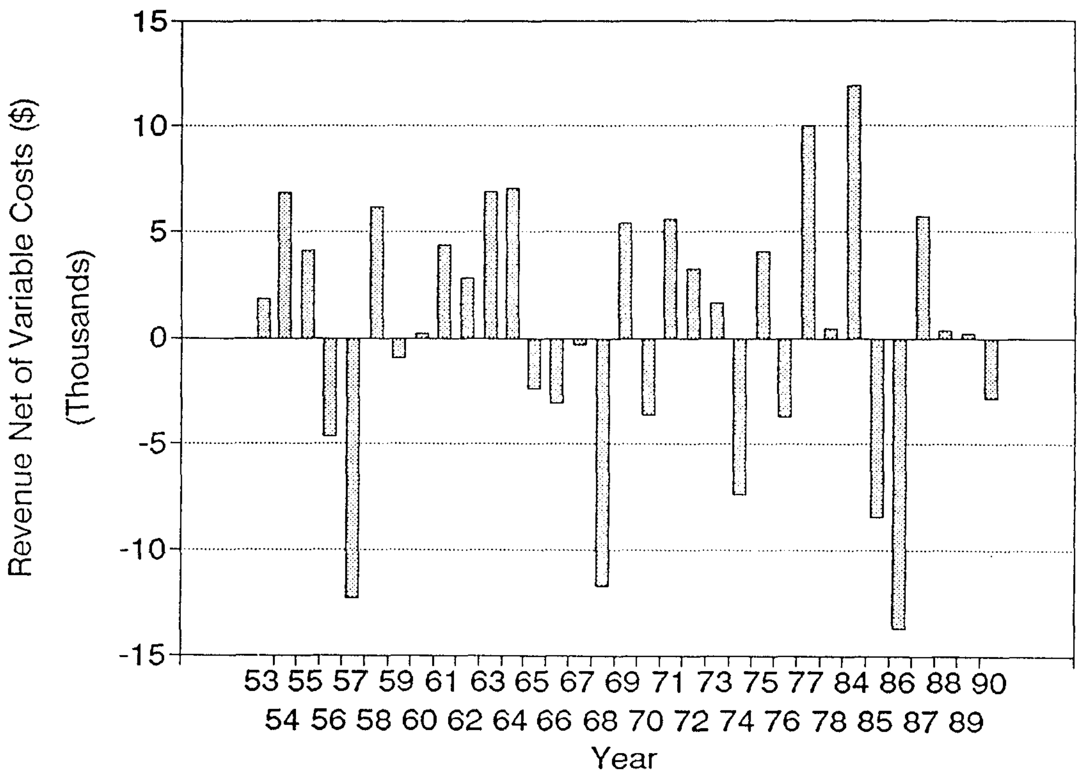


Figure 5.9

Revenue Net of Variable Costs, No-Till minus 45% Fall Plowed, on an Oshtemo Sandy Loam in Michigan, 1953-78, 1984-90.

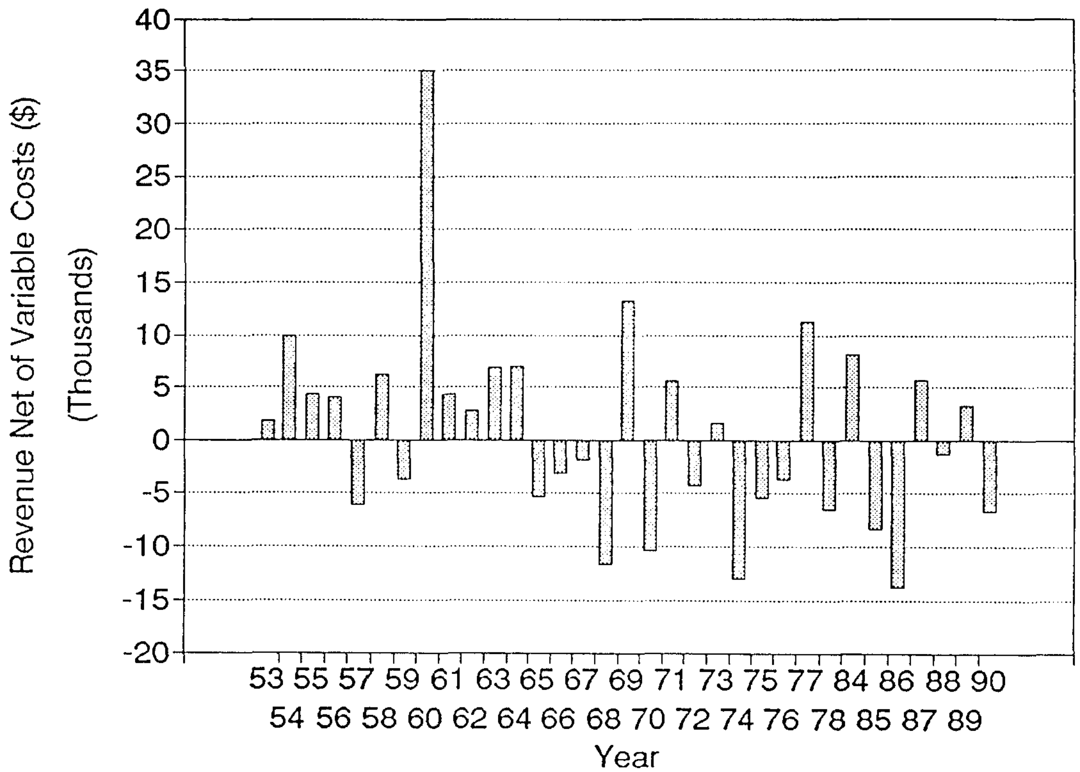


Figure 5.10

Net Revenue CDF's, No-Till and 100% Fall Plowed, on an Oshtemo Sandy Loam in Michigan, 1953-78, 1984-90.

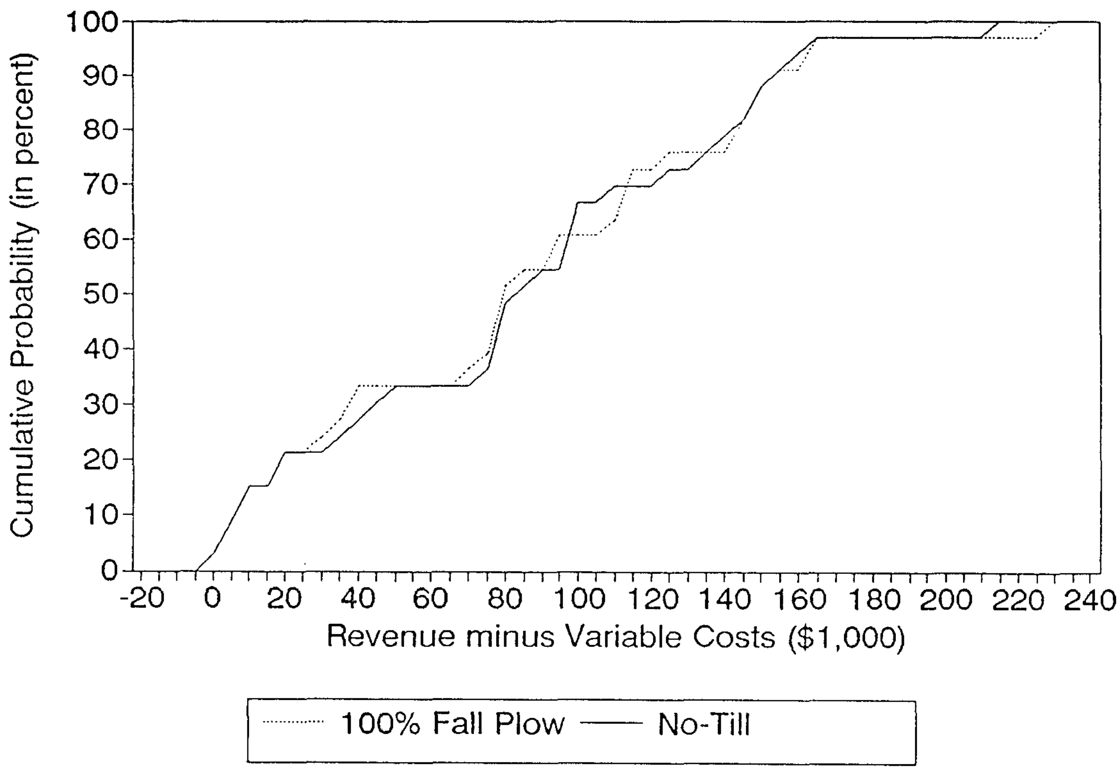


Figure 5.11

Net Revenue CDF's, No-Till and 70% Fall Plowed, on an Oshtemo Sandy Loam in Michigan, 1953-78, 1984-90.

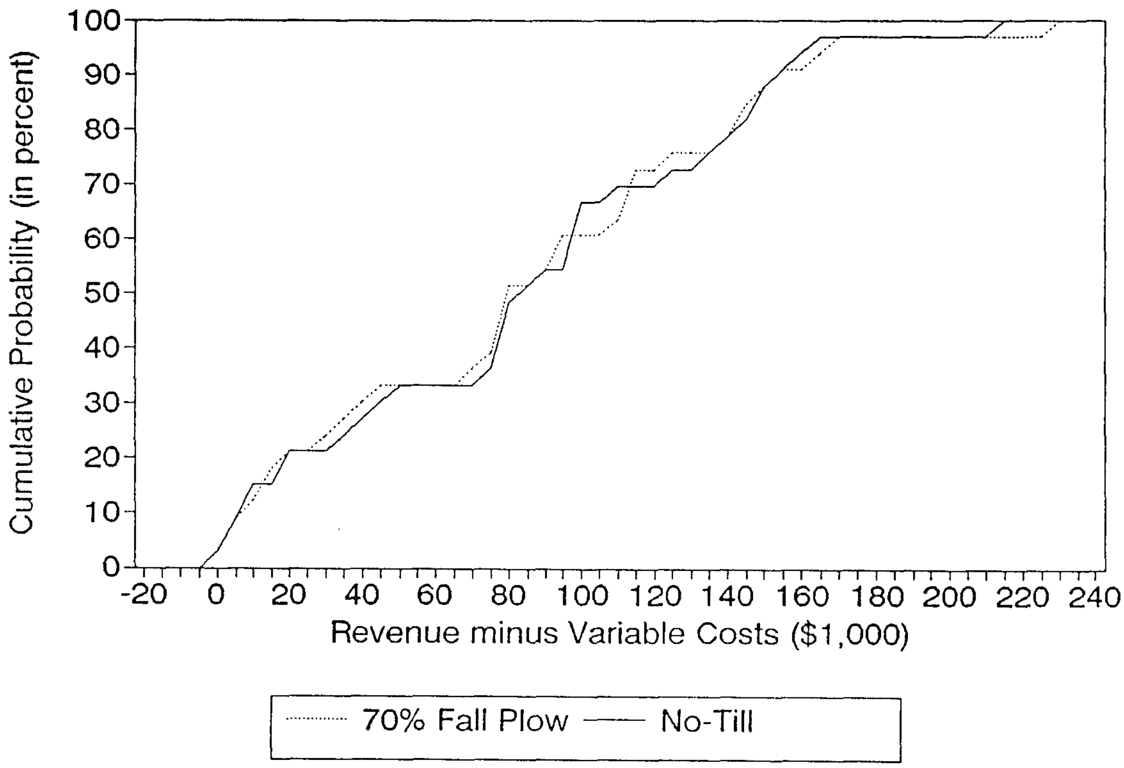
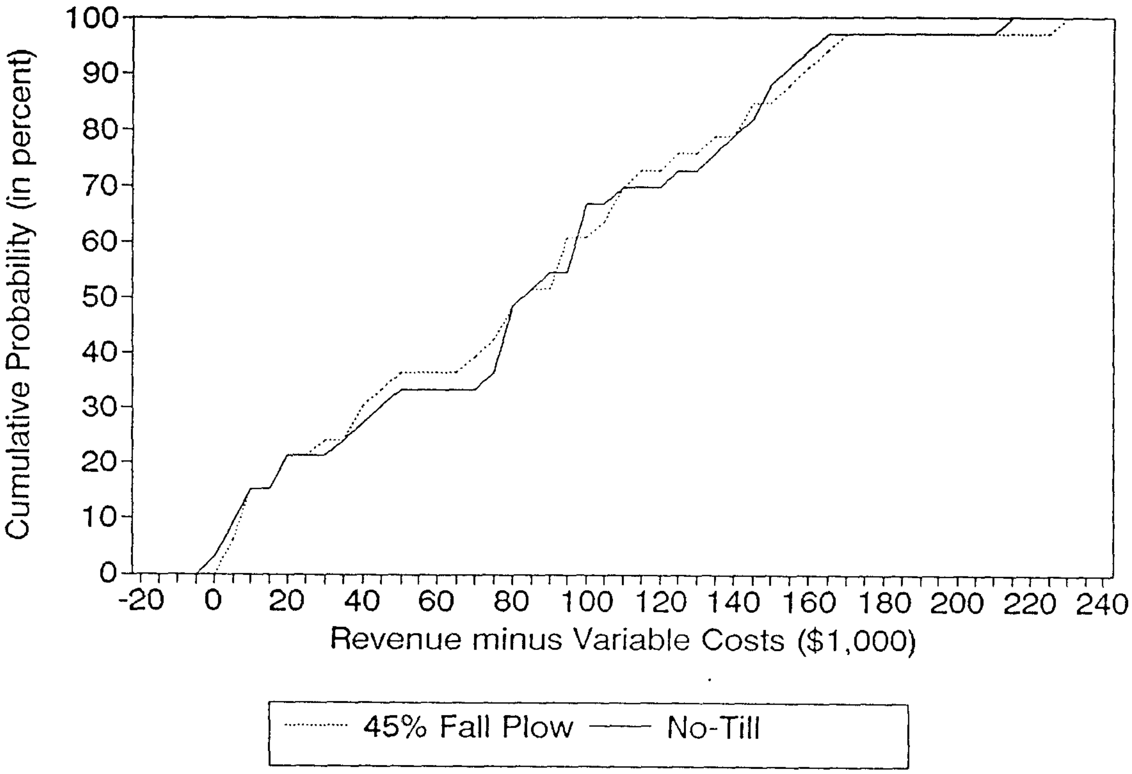


Figure 5.12

Net Revenue CDF's, No-Till and 45% Fall Plowed, on an Oshtemo Sandy Loam in Michigan, 1953-78, 1984-90.



Using long-term median corn and soybean prices, revenues net of variable costs[12] for the no-till system almost but do not quite exhibit second-degree stochastic dominance (SSD) over those for the conventional tillage system with the various levels of fall plowing. The no-till system would exhibit second-degree stochastic dominance over the conventional tillage system if the integral of the difference between the cumulative distribution function (CDF) for the conventional tillage system and the CDF for the no-till system is always non-negative. The graph of the CDF's of revenues net of variable costs for no-till and conventional tillage with 100% fall plowing (Figure 5.10) is not detailed enough to show that the lowest observation for no-till is about $198 less than the lowest observation for 100% fall plowing, but this violates SSD. The graphs of the CDF's of revenues net of variable costs for no-till and conventional tillage with 70% fall plowing (Figure 5.11) and 45% fall plowing (Figure 5.12) clearly show a range of net revenue values in the left tail of the CDF's for which this difference is negative, which violates SSD.

However, if all tillage implements not used under the no-till system were sold, a conservative estimate of annual fixed-cost savings of $3,078[13] would clearly make revenues net of both variable and fixed costs exhibit SSD for the no-till system over the conventional tillage

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[12] Again, repair costs for the planter and tractor are not included in these variable cost estimates because they change with accumulated usage.

[13] This includes annual fixed costs for shelter, insurance, taxes, and depreciation. Annual fixed costs for shelter, insurance, and taxes are estimated as 2.5% of purchase price (85% of list price), following Hunt (1983). Annual fixed costs for depreciation are estimated as 8% of list price, which is an extremely conservative estimate.

system. Second-degree stochastic dominance implies that all risk-averse individuals would prefer the choice that exhibits SSD (see Chapter 2). Consideration of fixed-cost savings would not make the no-till system exhibit first-degree stochastic dominance over conventional tillage, because their respective CDF's would still cross at around $100,000 net revenue and again at around $215,000 net revenue. First-degree stochastic dominance would imply that all individuals who prefer more net revenue to less would prefer the choice that exhibits FSD, regardless of their risk preferences.

Summary of Crop Yield and Static Economic Results

The no-till and moldboard plow tillage systems exhibit large variation in crop yields and net revenues, but the mean crop yields and mean revenues net of variable costs are very nearly equal. Mean revenues net of variable costs are slightly higher for the no-till system than for the moldboard plow system with any level of fall plowing completion. Variation in the proportion of plowing completed in the fall did not alter the essential equality in mean crop yields and mean revenues net of variable costs between the no-till and moldboard plow tillage systems. Indeed, net revenue results for 100% fall plowing, 70% fall plowing, and 45% fall plowing are so similar, that only the 70% fall plowing scenario which provided the highest net revenue results is evaluated in the dynamic programming analysis. Consideration of possible reductions in annual fixed costs greatly increases the difference in net profits between the no-till system and the moldboard plow tillage system.

There also is no clear difference in the riskiness of the no-till and moldboard plow systems, as measured by second-degree stochastic dominance, unless possible reductions in annual fixed costs are considered. When conservative estimates of reductions in annual fixed costs are considered, net revenues do exhibit second-degree stochastic dominance for the no-till system over the moldboard plow system. These results are very consistent with previous studies by Klemme (1985) and Williams (1988).

The near-equality of crop yields for the no-till and moldboard plow tillage system also is consistent with studies in Michigan by Bronson (1989) and Hesterman et al. (1988) which found no significant tillage effect on crop yields. The small effect of soybean planting date on the estimated mean soybean yields for different levels of fall plowing completion is somewhat surprising. Rotz et al. (1983) claim that soybean yields decline by 1% per day as planting is delayed after May 20. However, Rotz et al. (1983) only cite unpublished data to support this claim, and Johnson (1987) claims that there is little effect of planting date on soybean yield through the first week in July. The SOYGRO model, which was developed in Florida, appears to exhibit much less sensitivity to near-freezing temperatures in September than the CERES-MAIZE model. This may be a deficiency in the SOYGRO model that partly causes the lack of response in estimated soybean yields to late planting dates. However, modeling soybean yield response to low September temperatures was beyond the scope of this analysis.

Chapter 6

OPTIMAL ADOPTION STRATEGY RESULTS

In general, the results of the dynamic programming analyses tell a much more interesting story about no-till adoption than the static economic analyses presented in the previous chapter. The results of the dynamic analyses confirm that adoption of the no-till system is the optimal choice in the long run for the profit-maximizing farmer. The results of the dynamic analyses also confirm that adoption of the no-till system usually is the optimal choice in the long run for the risk-averse, expected utility-maximizing farmer, particularly when possible savings in machinery fixed costs are considered. But the dynamic programming results also show that machinery replacement issues, learning curves, and renting options all may play a role in determining the optimal timing of adoption and how machinery is acquired. The dynamic programming results also indicate that the optimal adoption strategies for the profit-maximizing farmer and the risk-averse, expected utility-maximizing farmer can be quite different.

This chapter presents the optimal adoption strategies for both the profit-maximizing and the risk-averse, expected utility-maximizing farmer. Optimal adoption strategies for the profit-maximizing farmer are solutions to the deterministic dynamic programming model, and are presented first. Optimal adoption strategies for the expected-utility maximizing farmer are solutions to the stochastic dynamic programming model, and are presented last. Because results for the stochastic dynamic programming model are conditional on the value of the stochastic price variable in each period, only the optimal policies for the first year are presented for this model.

Results are presented for different price, learning curve, discount rate, and crop yield assumptions. Optimal adoption strategies for the profit-maximizing farmer are presented both for historical median corn and soybean prices and for current (1991-92) prices. Optimal adoption strategies for the risk-averse, expected utility-maximizing farmer are presented for seven different current price states. The price states are based on the previous year's corn and soybean prices and determine probabilities for a range of possible prices in the current year[1]. The three learning curve assumptions are: (1) the 20% learning curve, in which herbicide, fuel and oil, labor, tractor repair, and planter repair costs are raised by 20% in the first year, 14% in the second year, and 7% in the third year of using the no-till system; (2) the 10% learning curve, in which each of these cost-inflation factors is reduced by one-half; and (3) no learning curve. Optimal adoption strategies are determined for both a 3% and a 6% discount rate. A few sensitivity analyses for optimal adoption strategies based on a 9% discount rate are also presented. The two crop yield assumptions are: (1) the yields estimated with CERES-MAIZE and SOYGRO for conventional tillage with 70% fall plowing and no-till; and (2) crop yields for both tillage systems set equal to those estimated for conventional tillage with 70% fall plowing.

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[1] Price states and their probabilities are explained in Chapters 3 and 4 and in Appendix B.

For both the deterministic and stochastic models, results are presented first for the case in which rental options are limited to renting a planter for the entire acreage of corn and soybeans at a price of $10 per acre plus a $320 delivery-retrieval fee. Presentation of the results is then repeated for the case in which farmers have the option to rent a no-till planter on 60 acres, 120 acres, or 180 acres for $10 per acre plus the delivery-retrieval fee of $320.

Results for the Deterministic Model

Limited Rental Options and Estimated Yields

The profit-maximizing farmer always adopts the no-till system in the first year if a 3% or 6% discount rate is used. The optimal adoption strategy is identical for the 20% learning curve, 10% learning curve, and no learning curve. The optimal adoption strategy also is identical for the historical mean prices of $2.80 per bushel of corn and $7.46 per bushel of soybeans, historical median prices of $2.66 for corn and $6.65 for soybeans, and the current prices of $2.30 for corn and $5.45 for soybeans. Provided that the 140 HP tractor has accumulated at least 1,600 hours of use, the optimal adoption strategy for a 6% discount rate is to immediately sell the conventional planter, purchase a no-till planter, sell the 140 HP tractor, and purchase the 85 HP tractor (Table 6.1). If the 140 HP tractor has not accumulated 1,600 hours of use, then only the planter is changed in the first year and the tractor is replaced when its accumulated use reaches 1,600 hours. The optimal adoption strategy is the same for a 3% discount rate except that

Table 6.1 Optimal Adoption Strategies based on Estimated Yields, Limited Renting Options, and a 6% Discount Rate.

Initial Ages* Planter (years)	Initial Ages* Tractor (hours)	Adoption Year	Purchases at Adoption**	Ages at Adoption Planter (years)	Ages at Adoption Tractor (hours)
1	800	1	PL 2	1	800
1	1600	1	PL 2 & TR 2	1	1600
1	2400	1	PL 2 & TR 2	1	2400
1	3200	1	PL 2 & TR 2	1	3200
1	4000	1	PL 2 & TR 2	1	4000
2	800	1	PL 2	2	800
2	1600	1	PL 2 & TR 2	2	1600
2	2400	1	PL 2 & TR 2	2	2400
2	3200	1	PL 2 & TR 2	2	3200
2	4000	1	PL 2 & TR 2	2	4000
4	800	1	PL 2	4	800
4	1600	1	PL 2 & TR 2	4	1600
4	2400	1	PL 2 & TR 2	4	2400
4	3200	1	PL 2 & TR 2	4	3200
4	4000	1	PL 2 & TR 2	4	4000
6	800	1	PL 2	6	800
6	1600	1	PL 2 & TR 2	6	1600
6	2400	1	PL 2 & TR 2	6	2400
6	3200	1	PL 2 & TR 2	6	3200
6	4000	1	PL 2 & TR 2	6	4000
8	800	1	PL 2	8	800
8	1600	1	PL 2 & TR 2	8	1600
8	2400	1	PL 2 & TR 2	8	2400
8	3200	1	PL 2 & TR 2	8	3200
8	4000	1	PL 2 & TR 2	8	4000
10	800	1	PL 2	10	800
10	1600	1	PL 2 & TR 2	10	1600
10	2400	1	PL 2 & TR 2	10	2400
10	3200	1	PL 2 & TR 2	10	3200
10	4000	1	PL 2 & TR 2	10	4000

* Optimal strategies for older planters and tractors are identical to those for the oldest planter and tractor shown, except that the machinery ages at adoption are higher.

** PL 2 is the no-till planter and TR 2 is the 85 HP tractor.

the 140 HP tractor is kept until it has accumulated at least 2,400 hours of use.

The profit-maximizing farmer occasionally waits one year before adopting the no-till system if a 9% discount rate is used and a 20% learning curve is expected. If historical median prices are expected, the initial planter age is at least 4 years, and the initial tractor age is less than 1,200 hours, the optimal strategy is to wait until the tractor has accumulated 1,200 hours, and then replace both the planter and the tractor (Table 6.2). If the current prices are expected to continue, the optimal adoption strategy is generally to wait until the tractor has accumulated 1,600 hours before replacing both the planter and the tractor. However, with a 10% learning curve and a 9% discount rate, the profit-maximizing farmer only delays adoption if current prices are expected, the tractor has accumulated 800 hours or less, and the planter is between 5 and 9 years old. If the historical median prices are expected or if no learning curve is expected, the profit-maximizing farmer with a 9% discount rate adopts the no-till system in the first year.

Limited Rental Options and Equal Yields

If equal crop yields for conventional tillage and no-till and a 20% learning curve are expected, the profit-maximizing farmer usually waits to adopt the no-till system until the tractor has accumulated at least 3,600 hours of use or the planter is more than 15 years old. Although there are a few exceptions (shown in Figure 6.1), these usually are the conditions for adoption with a 3% discount rate. If the planter

Table 6.2 Optimal Adoption Strategies for Current Prices, Limited Renting Options, a 20% Learning Curve, and a 9% Discount Rate.

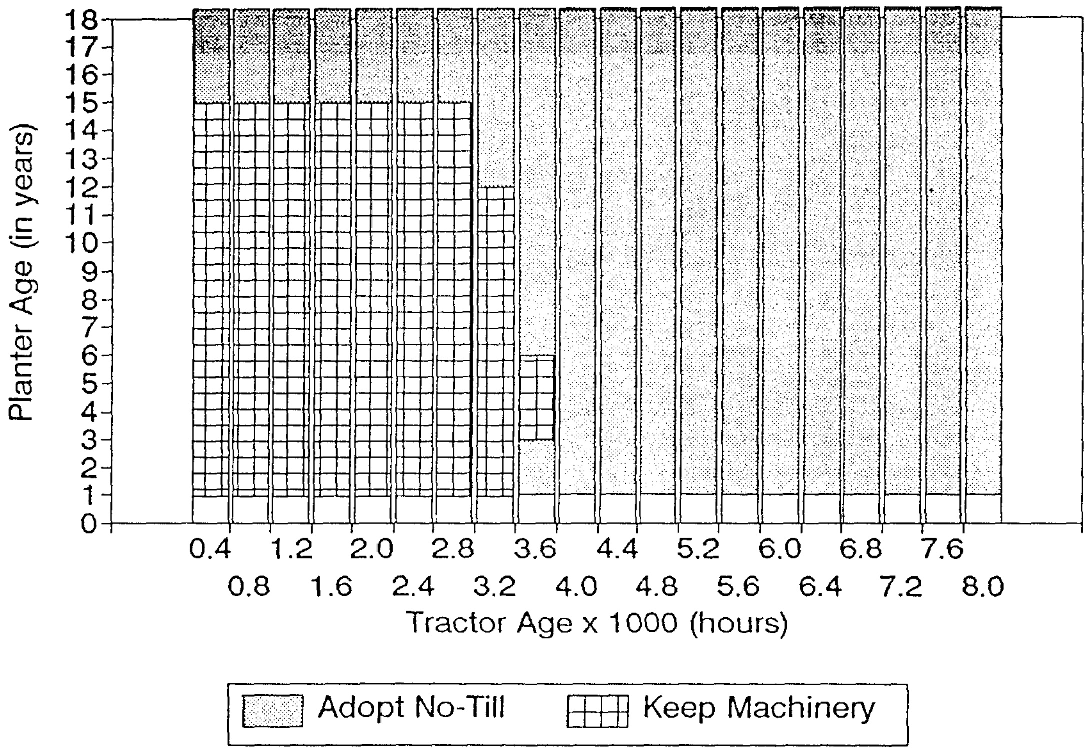
Initial Ages* Planter (years)	Initial Ages* Tractor (hours)	Adoption Year	Purchases at Adoption**	Ages at Adoption Planter (years)	Ages at Adoption Tractor (hours)
1	800	1	PL 2 & TR 2	1	800
1	1600	1	PL 2 & TR 2	1	1600
1	2400	1	PL 2 & TR 2	1	2400
2	800	1	PL 2 & TR 2	2	800
2	1600	1	PL 2 & TR 2	2	1600
2	2400	1	PL 2 & TR 2	2	2400
4	800	2	PL 2 & TR 2	5	1600
4	1600	1	PL 2 & TR 2	4	1600
4	2400	1	PL 2 & TR 2	4	2400
6	800	2	PL 2 & TR 2	7	1600
6	1600	1	PL 2 & TR 2	6	1600
6	2400	1	PL 2 & TR 2	6	2400
8	800	2	PL 2 & TR 2	9	1600
8	1600	1	PL 2 & TR 2	8	1600
8	2400	1	PL 2 & TR 2	8	2400
10	800	2	PL 2 & TR 2	11	1600
10	1600	1	PL 2 & TR 2	10	1600
10	2400	1	PL 2 & TR 2	10	2400
12	800	1	PL 2 & TR 2	12	800
12	1600	1	PL 2 & TR 2	12	1600
12	2400	1	PL 2 & TR 2	12	2400
14	800	1	PL 2 & TR 2	14	800
14	1600	1	PL 2 & TR 2	14	1600
14	2400	1	PL 2 & TR 2	14	2400

* Optimal strategies for older planters and tractors are identical to those for the oldest planter and tractor shown, except that the machinery ages at adoption are higher.

** PL 2 is the no-till planter and TR 2 is the 85 HP tractor.

Figure 6.1

Profit-Maximizing Policies for Equal Yields, a 3% Discount Rate, a 20% Learning Curve, and Various Machinery Ages.



reaches 16 years of age before the tractor accumulates 2,800 hours, the optimal strategy is to only replace the conventional planter with the no-till planter. Otherwise, the optimal strategy is to replace both the conventional planter with the no-till planter and 140 HP tractor with the 85 HP tractor. With a 6% discount rate, the profit-maximizing farmer usually waits until either the tractor has accumulated at least 4,000 hours or the planter is more than 16 years old before adopting the no-till system (Figure 6.2). The profit-maximizing farmer with a 6% discount rate will replace both the tractor and planter at the same time if the tractor has accumulated at least 1,600 hours. These optimal adoption strategies are identical for the expectation of historical median prices or current prices for corn and soybeans.

If a 10% or zero learning curve are expected, the profit-maximizing farmer often will adopt the no-till system one or two years earlier than if the 20% learning curve is expected. With a 10% learning curve and 3% discount rate, the profit-maximizing farmer will adopt the no-till system if the tractor has accumulated 3,200 hours of use and the planter is more than 9 years old, or for any planter age if the tractor has accumulated 3,600 hours of use. With a zero learning curve and 3% discount rate, the minimum planter age for no-till adoption by the profit-maximizing farmer is reduced, and drops to one year if the tractor has accumulated 3,200 hours (Figure 6.3). With a 6% discount rate, the profit-maximizing farmer will always adopt the no-till system if the tractor has accumulated 3,600 hours and a 10% learning curve is expected or if the tractor has accumulated 3,200 hours and no learning

Figure 6.2

Profit-Maximizing Policies for Equal Yields, a 6% Discount Rate, a 20% Learning Curve, and Various Machinery Ages.

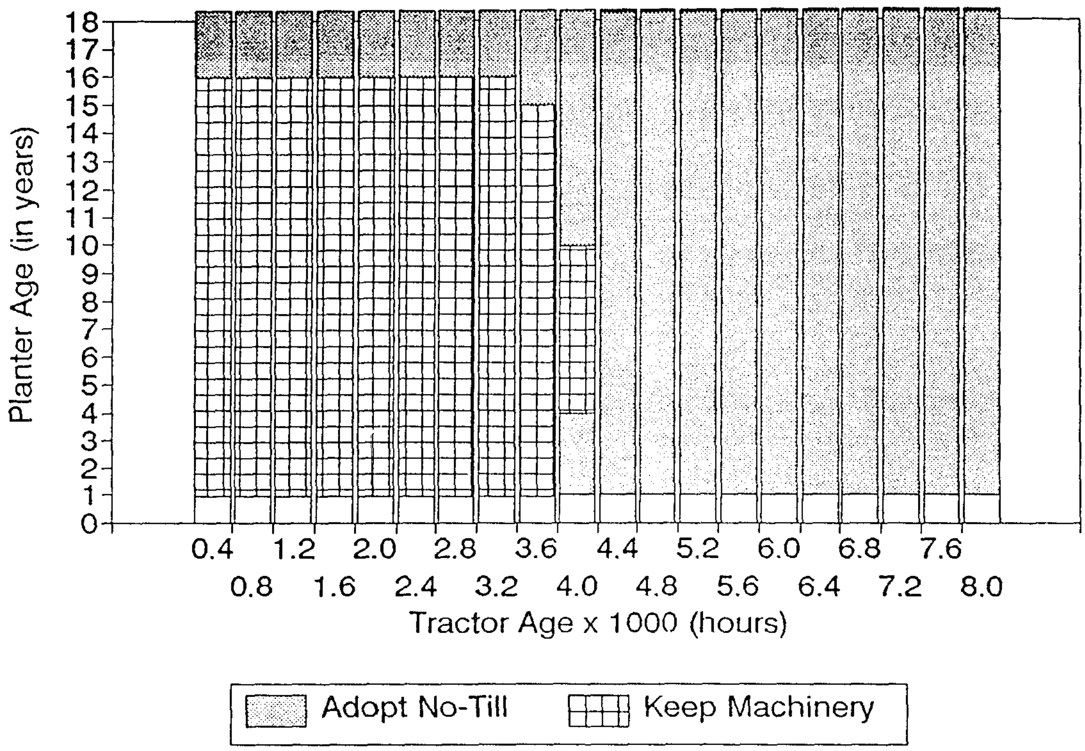
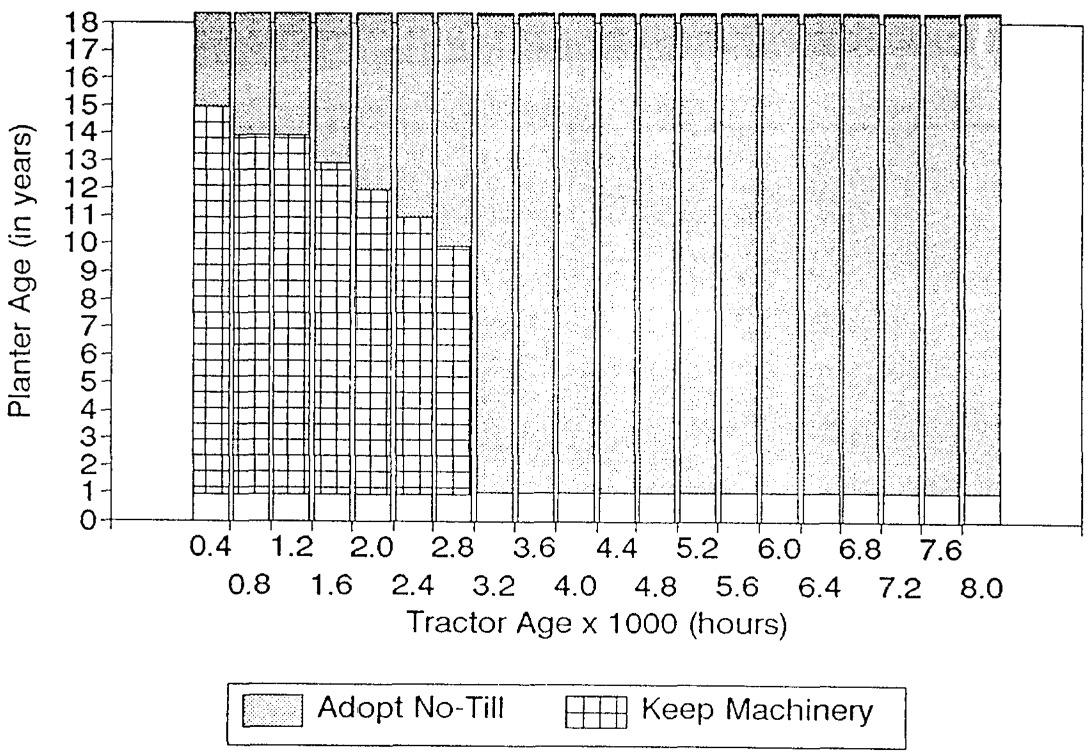


Figure 6.3

Profit-Maximizing Policies for Equal Yields, a 3% Discount Rate, No Learning Curve, and Various Machinery Ages.



curve is expected. These results also are not affected by whether the historical median or current corn and soybean prices are expected.

Multiple Renting Options and Estimated Crop Yields

When the farmer is allowed to rent the no-till planter on 60, 120, or 240 acres and a 20% learning curve is expected, the profit-maximizing farmer usually rents the no-till planter to plant 60 acres for one or two years before purchasing the no-till planter (Tables 6.3, 6.4, and 6.5). This corresponds to the frequently recommended practice of trying a new technology out on a limited acreage, both for evaluation and for learning how to make it work more effectively before full-scale adoption. However, if the 10% learning curve or no learning curve is expected, the optimal adoption strategy usually is to ignore rental possibilities and follow the optimal strategy determined above for limited renting options[2]. Also, after the tractor has accumulated more than 3,200 hours, the optimal adoption strategy is to immediately replace the 140 HP tractor with the 85 HP tractor and purchase the no-till planter. This implies that once repair costs for the 140 HP tractor have risen to moderately high levels, the benefit of limiting the costs of learning the no-till technology to a small acreage is outweighed by the benefit of reducing repair costs by switching to a new 85 HP tractor.

[2] There are a very few cases when current prices and a 10% learning curve are expected for which the profit-maximizing farmer will rent the no-till planter for one year before adopting no-till. For example, with a 6% discount rate the optimal policy is to rent the no-till planter on 60 acres if the tractor age is 800 hours and the planter age is 6-10 years.

Table 6.3 Optimal Adoption Strategies for Median Prices, Multiple Renting Options, a 20% Learning Curve, and a 3% Discount Rate.

Initial Ages* Planter (years)	Initial Ages* Tractor (hours)	Adoption Year	Purchases at Adoption**	Ages at Adoption Planter (years)	Ages at Adoption Tractor (hours)	Years Rented
2	800	2	PL 2	3	1600	1
2	1600	2	PL 2	3	2400	1
2	2400	2	PL 2 & TR 2	3	3200	1
2	3200	1	PL 2 & TR 2	2	3200	0
2	4000	1	PL 2 & TR 2	2	4000	0
4	800	2	PL 2	5	1600	1
4	1600	2	PL 2	5	2400	1
4	2400	2	PL 2 & TR 2	5	3200	1
4	3200	2	PL 2 & TR 2	5	4000	1
4	4000	1	PL 2 & TR 2	4	4000	0
6	800	2	PL 2 & TR 2	7	2400	1
6	1600	2	PL 2 & TR 2	7	2400	1
6	2400	2	PL 2 & TR 2	7	3200	1
6	3200	2	PL 2 & TR 2	7	4000	1
6	4000	1	PL 2 & TR 2	6	4000	0
8	800	2	PL 2 & TR 2	9	1600	1
8	1600	2	PL 2 & TR 2	9	2400	1
8	2400	2	PL 2 & TR 2	9	3200	1
8	3200	2	PL 2 & TR 2	9	4000	1
8	4000	1	PL 2 & TR 2	8	4000	0
10	800	2	PL 2 & TR 2	11	1600	1
10	1600	2	PL 2 & TR 2	11	2400	1
10	2400	2	PL 2 & TR 2	11	3200	1
10	3200	1	PL 2 & TR 2	10	3200	0
10	4000	1	PL 2 & TR 2	10	4000	0

* Optimal strategies for older planters (up to 16 years) and tractors (up to 9600 hours) are identical to those for the oldest planter and tractor shown, except that the planter and tractor ages at adoption are higher.

** PL 2 is the no-till planter and TR 2 is the 85 HP tractor.

Table 6.4 Optimal Adoption Strategies for Median Prices, Multiple Renting Options, a 20% Learning Curve, and a 6% Discount Rate.

Initial Ages*			Purchases	Ages at Adoption		
Planter (years)	Tractor (hours)	Adoption Year	at Adoption**	Planter (years)	Tractor (hours)	Years Rented
2	800	3	PL 2 & TR 2	4	2400	2
2	1600	2	PL 2 & TR 2	3	2400	1
2	2400	2	PL 2 & TR 2	2	3200	1
2	3200	1	PL 2 & TR 2	2	3200	0
4	800	3	PL 2 & TR 2	6	2400	2
4	1600	2	PL 2 & TR 2	5	2400	1
4	2400	2	PL 2 & TR 2	5	3200	1
4	3200	1	PL 2 & TR 2	4	3200	0
6	800	3	PL 2 & TR 2	8	2400	2
6	1600	2	PL 2 & TR 2	7	2400	1
6	2400	2	PL 2 & TR 2	7	3200	1
6	3200	1	PL 2 & TR 2	6	3200	0
8	800	3	PL 2 & TR 2	10	2400	2
8	1600	2	PL 2 & TR 2	9	2400	1
8	2400	2	PL 2 & TR 2	9	3200	1
8	3200	1	PL 2 & TR 2	8	3200	0
10	800	3	PL 2 & TR 2	12	2400	2
10	1600	2	PL 2 & TR 2	11	2400	1
10	2400	2	PL 2 & TR 2	11	3200	1
10	3200	1	PL 2 & TR 2	10	3200	0

* Optimal strategies for older planters (up to 16 years) and tractors (up to 9600 hours) are identical to those for the oldest planter and tractor shown, except that the planter and tractor ages at adoption are higher.

** PL 2 is the no-till planter and TR 2 is the 85 HP tractor.

Table 6.5 Optimal Adoption Strategies for Current Prices, Multiple Renting Options, a 20% Learning Curve, and a 6% Discount Rate.

Initial Ages* Planter (years)	Initial Ages* Tractor (hours)	Adoption Year	Purchases at Adoption**	Ages at Adoption Planter (years)	Ages at Adoption Tractor (hours)	Years Rented
2	800	3	PL 2 & TR 2	4	2400	2
2	1600	2	PL 2 & TR 2	3	2400	1
2	2400	2	PL 2 & TR 2	3	3200	1
2	3200	2	PL 2 & TR 2	3	4000	1
2	4000	1	PL 2 & TR 2	2	4000	0
4	800	3	PL 2 & TR 2	6	2400	2
4	1600	2	PL 2 & TR 2	5	2400	1
4	2400	2	PL 2 & TR 2	5	3200	1
4	3200	2	PL 2 & TR 2	5	3200	1
4	4000	1	PL 2 & TR 2	4	4000	0
6	800	3	PL 2 & TR 2	8	2400	2
6	1600	2	PL 2 & TR 2	7	2400	1
6	2400	2	PL 2 & TR 2	7	3200	1
6	3200	2	PL 2 & TR 2	7	4000	1
6	4000	1	PL 2 & TR 2	6	4000	0
8	800	3	PL 2 & TR 2	10	2400	2
8	1600	2	PL 2 & TR 2	9	2400	1
8	2400	2	PL 2 & TR 2	9	3200	1
8	3200	2	PL 2 & TR 2	9	4000	1
8	4000	1	PL 2 & TR 2	8	4000	0
10	800	3	PL 2 & TR 2	12	2400	2
10	1600	2	PL 2 & TR 2	11	2400	1
10	2400	2	PL 2 & TR 2	11	3200	1
10	3200	2	PL 2 & TR 2	11	4000	1
10	4000	1	PL 2 & TR 2	10	4000	0

* Optimal strategies for older planters and tractors are identical to those for the oldest planter and tractor shown, except that the machinery ages at adoption are higher.

** PL 2 is the no-till planter and TR 2 is the 85 HP tractor.

Optimal adoption strategies when multiple renting options are available vary slightly for different discount rates and crop prices. When the discount rate is increased from 3% (Table 6.3) to 6% (Table 6.4) and historical median prices are expected, the profit-maximizing farmer usually rents the no-till planter one additional year if the initial tractor age is 800 hours or 3200 hours. The profit-maximizing farmer also rents the no-till planter one additional year if the tractor age is 3200 hours and the current corn and soybean prices are expected (Table 6.5) rather than the historical median prices (Table 6.4).

Multiple Renting Options and Equal Crop Yields

If a 20% learning curve and equal crop yields for the two tillage systems are expected, the profit-maximizing farmer often rents the no-till planter to plant 60 acres for one or two years before buying the no-till planter (Table 6.6). The profit-maximizing farmer rents the no-till planter for a wider range of planter and tractor ages when equal yields for the two tillage systems are expected than when the estimated crop yields are expected (compare Table 6.6 to Table 6.3). Under the optimal adoption strategy, the 140 HP tractor is replaced with the 85 HP tractor at the same time as the conventional planter is replaced with the no-till planter.

However, with a 10% learning curve and 6% discount rate, the profit-maximizing farmer only rents the no-till planter if the tractor age is less than 1,600 hours and planter age is less than 16 years (regardless of price expectations). With a 10% learning curve and 6% discount rate, the profit-maximizing farmer also occasionally rents the

Table 6.6 Optimal Adoption Strategies for Equal Yields, Median Prices Multiple Renting Options, a 20% Learning Curve, and a 6% Discount Rate.

Initial Ages*			Purchases	Ages at Adoption		
Planter (years)	Tractor (hours)	Adoption Year	at Adoption**	Planter (years)	Tractor (hours)	Years Rented
2	800	4	PL 2 & TR 2	5	3200	2
2	1600	3	PL 2 & TR 2	4	3200	2
2	2400	3	PL 2 & TR 2	4	4000	2
2	3200	2	PL 2 & TR 2	3	4000	1
2	4000	2	PL 2 & TR 2	3	4800	1
2	4800	2	PL 2 & TR 2	3	5200	1
2	5200	1	PL 2 & TR 2	2	5200	0
4	800	4	PL 2 & TR 2	7	3200	2
4	1600	3	PL 2 & TR 2	6	3200	2
4	2400	3	PL 2 & TR 2	6	4000	2
4	3200	2	PL 2 & TR 2	5	4000	1
4	4000	2	PL 2 & TR 2	5	4800	1
4	4800	2	PL 2 & TR 2	4	5200	1
4	5200	1	PL 2 & TR 2	4	5200	0
8	800	4	PL 2 & TR 2	11	3200	2
8	1600	3	PL 2 & TR 2	10	3200	2
8	2400	3	PL 2 & TR 2	10	4000	2
8	3200	2	PL 2 & TR 2	9	4000	1
8	4000	2	PL 2 & TR 2	9	4800	1
8	4800	2	PL 2 & TR 2	9	5200	1
8	5200	1	PL 2 & TR 2	8	5200	0
12	800	3	PL 2 & TR 2	14	2400	2
12	1600	3	PL 2 & TR 2	14	3200	2
12	2400	3	PL 2 & TR 2	14	4000	2
12	3200	2	PL 2 & TR 2	13	4000	1
12	4000	2	PL 2 & TR 2	13	4800	1
12	4800	2	PL 2 & TR 2	13	5200	1
12	5200	1	PL 2 & TR 2	12	5200	0

* This is a representative sample of initial ages. Renting is limited to initial tractor ages less than 3200 hours if the initial planter age is 16 years.

** PL 2 is the no-till planter and TR 2 is the 85 HP tractor.

no-till planter when the tractor age is 2,000 hours. With no learning curve, the profit-maximizing farmer never rents the no-till planter.

An interesting result is that if the initial tractor and planter ages are no more than 800 hours and 10 years, respectively, the optimal adoption strategy is to keep the initial machinery in the third year without renting (Table 6.6). The 20% learning curve raises herbicide, fuel, labor, tractor repair, and planter repair cost by only 3.5% after 2 years of experience. This implies that the rental fee of $10 per acre plus a $320 delivery-retrieval fee outweighs the benefit of incurring the remaining learning costs for the no-till system on only 60 acres versus 600 acres.

If a 20% learning curve is expected, the opportunity to rent the no-till planter on a small proportion of the corn and soybean acres slightly accelerates adoption if the initial tractor age is less than 3600 hours. However, this opportunity delays full adoption by the profit-maximizing farmer if the initial tractor age is 4400-4800 hours and has no effect if the initial tractor age is more than 4800 hours. This result suggests that it may not be an optimal strategy for machinery dealers to attempt to increase sales of no-till equipment by making it more convenient and less expensive to rent no-till planters. However, this result depends on the not very realistic assumption that the farmer is certain that he or she knows what the expected crop yield will be on his or her farm. In practice, the farmer probably experiments with a new technology just as much to discover what the expected results would be as to learn how to reduce costs (or equivalently, increase crop yields) for that technology.

Results for the Stochastic Model

Limited Renting Options and Estimated Crop Yields

The optimal adoption strategies for the risk-averse, expected utility-maximizing farmer clearly indicate that risk aversion may greatly delay the adoption of the no-till technology. Using probability expectations for crop prices that correspond to the historical mean prices of $2.80 for corn and $7.46 for soybeans, there are many combinations of initial planter age, tractor age, and price state for which the expected utility-maximizing farmer will keep the conventional planter and 140 HP tractor. Most of these cases include the first price state of low corn and low soybean prices in the previous year. Since the probability of continued low prices for the current price state of low corn and low soybean prices is very high[2], the optimal risk-averse strategy is to postpone machinery investments when crop prices are low.

With a 6% discount rate and moderate risk aversion, the expected utility-maximizing farmer usually keeps the initial machinery in price state 1 unless the planter is more than 15 years old or the tractor has accumulated more than 8,000 hours of use (Figure 6.4). Under price state 3, the expected utility-maximizing farmer usually will change to the no-till planter if the tractor has accumulated less than 3,600 hours or more than 6,400 hours (Figure 6.5). Otherwise, the expected utility-maximizing farmer usually keeps the conventional planter until it is about 15 years old or until the tractor accumulates more than 6,400 hours. Also, in price state 2, if the tractor has accumulated exactly

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[2] For example, the probability that price state 1 will be followed by price state 1 is set at 70% (see Chapter 4).

Figure 6.4

Optimal Policies for Moderate Risk Aversion, a 6% Discount Rate, Estimated Yields, and Price State 1.

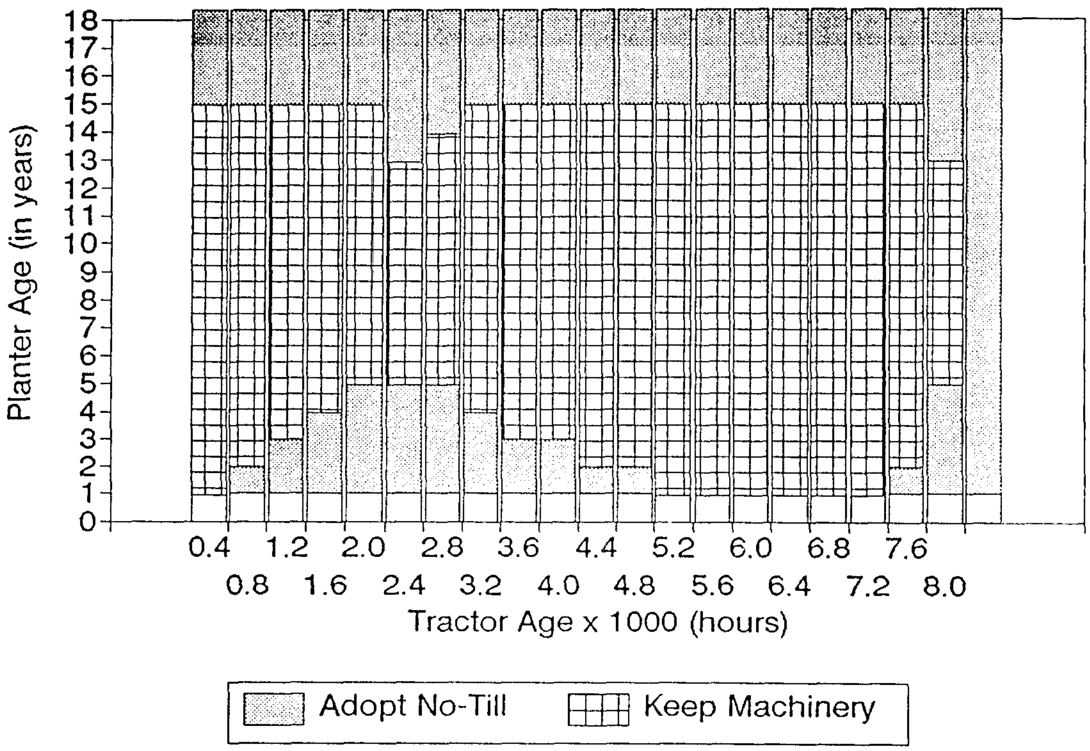
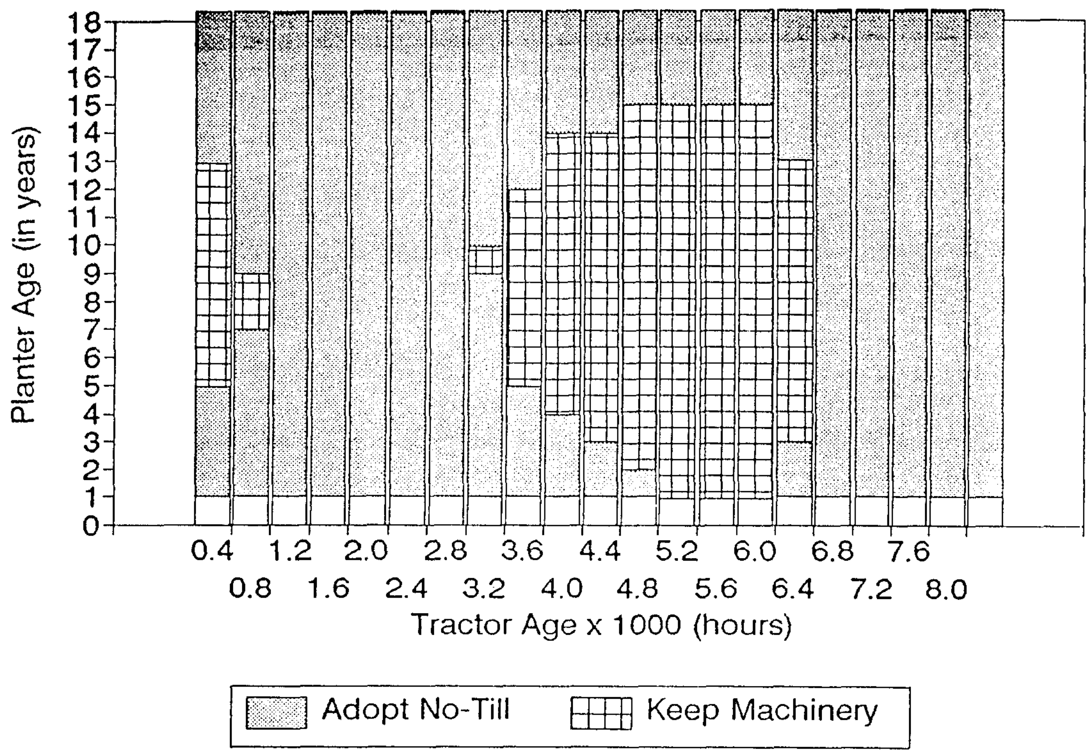


Figure 6.5

Optimal Policies for Moderate Risk Aversion, a 6% Discount Rate, Estimated Yields, and Price State 3.



3,200 hours and the planter is 7-11 years old, the optimal policy is to keep the initial machinery. Similarly, in price state 4, if the tractor has accumulated exactly 3,200 hours and the planter is 8-11 years old, the optimal policy is to keep the initial machinery. Otherwise and in the other price states, the optimal policy for a 6% discount rate and moderate risk aversion is to immediately adopt the no-till system.

In contrast to the optimal adoption strategies for the profit-maximizing farmer, the risk-averse, expected utility-maximizing farmer rarely purchases the no-till planter and 85 HP tractor in the same year. Furthermore, the expected utility-maximizing farmer often chooses to rent the no-till planter on all 600 acres of corn and soybeans rather than purchase the no-till planter. This is especially true in the price states with relatively high corn and soybean prices, price states 5-7, and when the tractor has accumulated more than 6,000 hours. However, the difference in expected utility between renting the no-till tractor and purchasing the no-till tractor usually is small when renting is selected.

The optimal adoption strategy for the expected utility-maximizing farmer is sensitive to the degree of risk aversion. A reduction in the relative risk aversion coefficient from 1.0 to 0.5 increases the number of cases for which the optimal strategy is to sell the conventional planter and either purchase or rent the the no-till planter (compare Figures 6.6 and 6.7 to Figures 6.4 and 6.5). When the risk aversion coefficient is set at zero (risk neutrality), the optimal strategy is to adopt no-till for every combination of planter age, tractor age, and price state, just as in the results for the deterministic model.

Figure 6.6

Optimal Policies for Slight Risk Aversion, a 6% Discount Rate, Estimated Yields, and Price State 1.

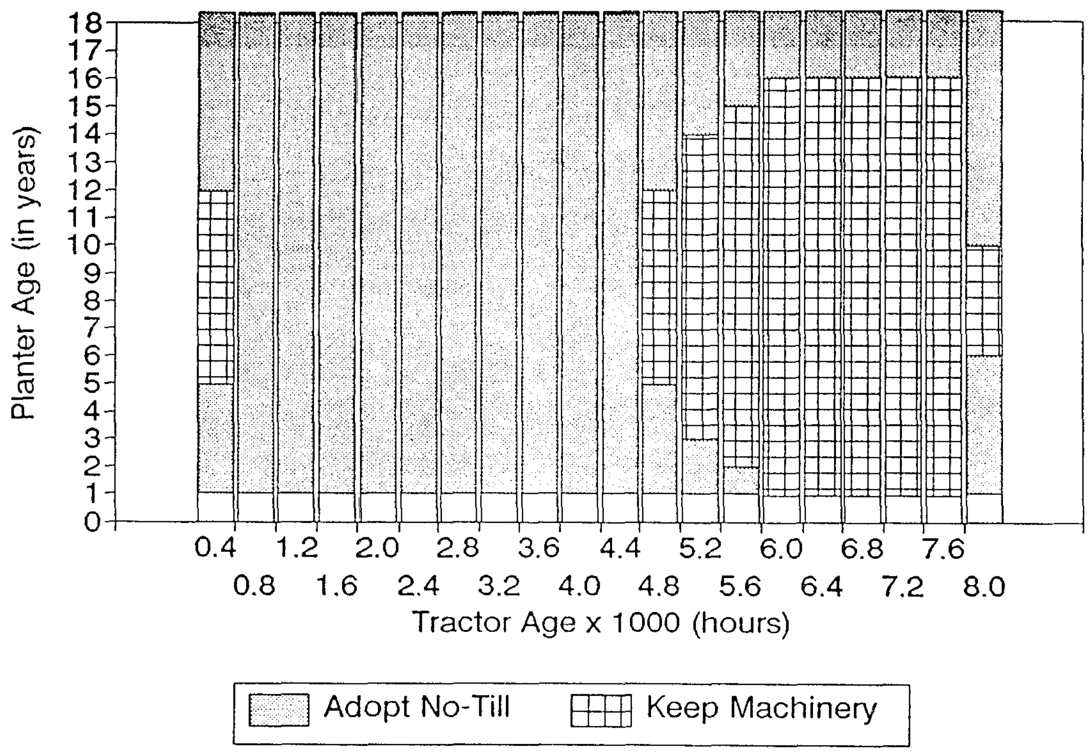
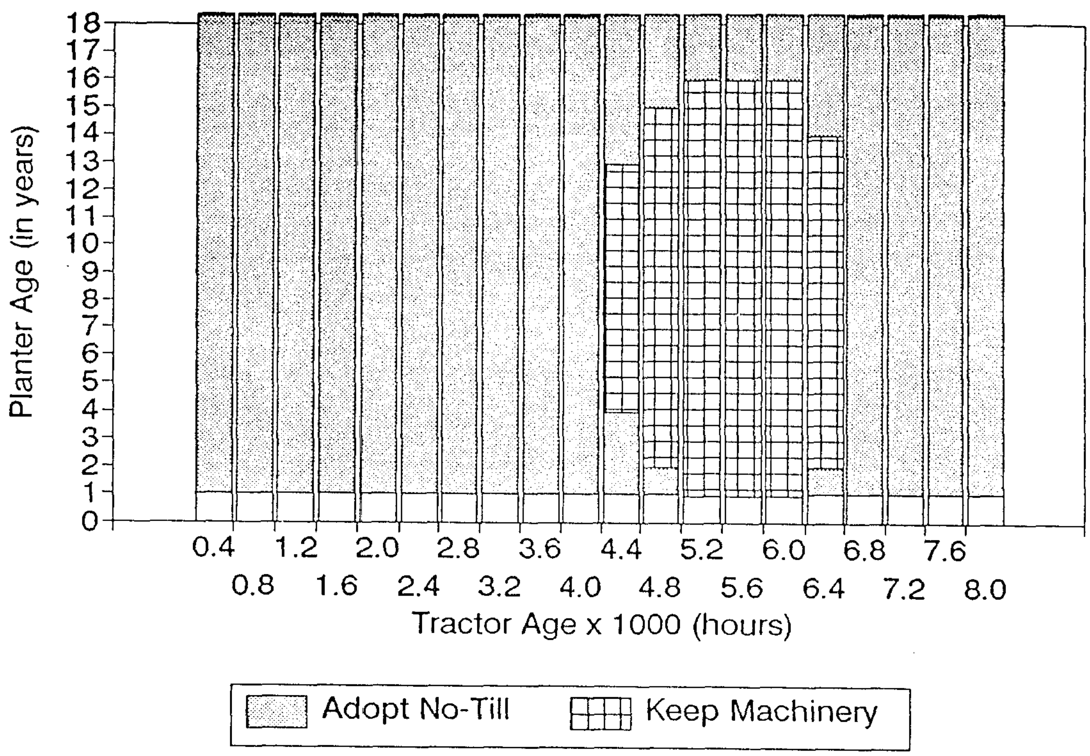


Figure 6.7

Optimal Policies for Slight Risk Aversion, a 6% Discount Rate, Estimated Yields, and Price State 3.



The optimal adoption strategy for the risk-averse, expected utility-maximizing farmer also is sensitive to the discount rate. Reducing the discount rate from 6% to 3% increases the number of cases for which the optimal policy for risk-averse farmers is to adopt the no-till system in the first year (compare Figures 6.8-6.11 to Figures 6.4-6.7). However, the results of the stochastic dynamic programming model for a 3% discount rate should be viewed with some caution because of the 30-year planning horizon used in the stochastic analyses. Any loss in value caused by having to sell equipment at the end of 30 years is much more heavily weighted with a 3% discount rate than with a 6% discount rate.

The number of cases for which the expected utility-maximizing farmer adopts the no-till system also increases slightly when using price state probabilities that roughly correspond to the historical median corn and soybean prices[4] (Compare Figures 6.12-6.15 to Figures 6.4-6.7). Thus, reducing crop prices for the risk-averse, expected utility-maximizing farmer has the opposite effect to reducing crop prices for the profit-maximizing farmer. However, prices were reduced for the expected utility-maximizing farmer by reducing the probabilities of the highest crop prices, which has the effect of reducing price variance. It therefore appears that stabilizing crop prices, even at slightly lower levels, may encourage risk-averse farmers to adopt the no-till technology.

[4] Probability weights were adjusted such that 50,000 random draws using 20 different random number seeds resulted in an average corn price of $2.63 and average soybean price of $6.70 (see Chapter 4 and Appendix B). These average prices are very close to the historical median prices of $2.66 for corn and $6.65 for soybeans.

Figure 6.8

Optimal Policies for Moderate Risk Aversion, a 3% Discount Rate, Estimated Yields, and Price State 1.

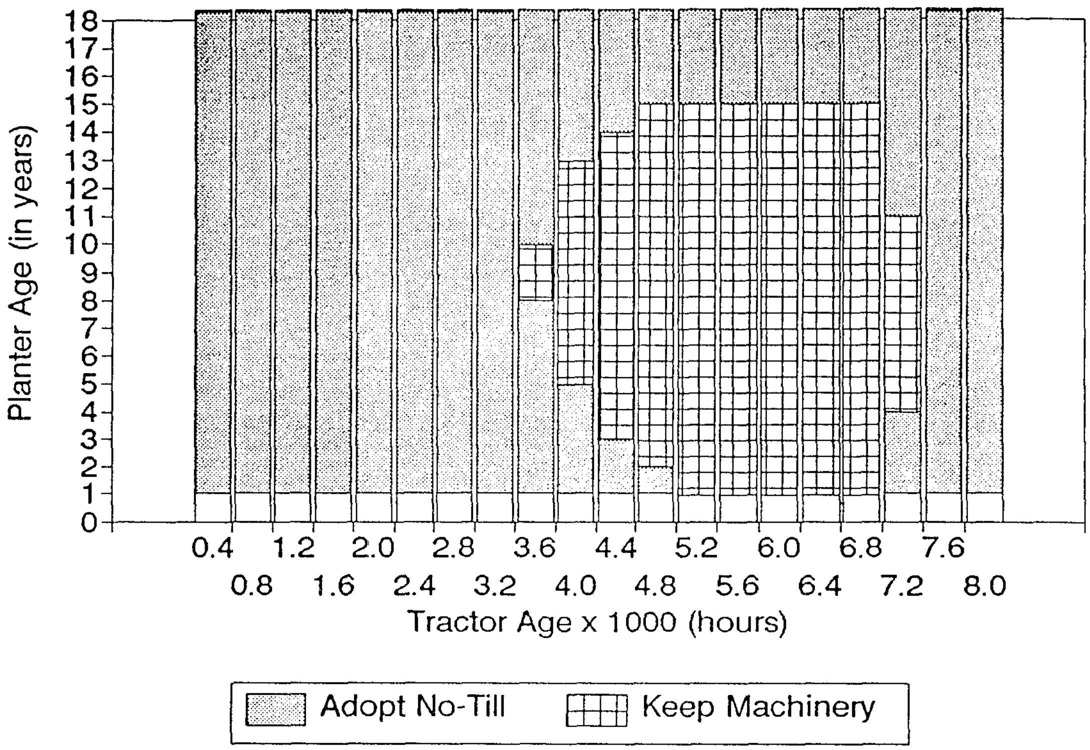


Figure 6.9

Optimal Policies for Moderate Risk Aversion, a 3% Discount Rate, Estimated Yields, and Price State 3.

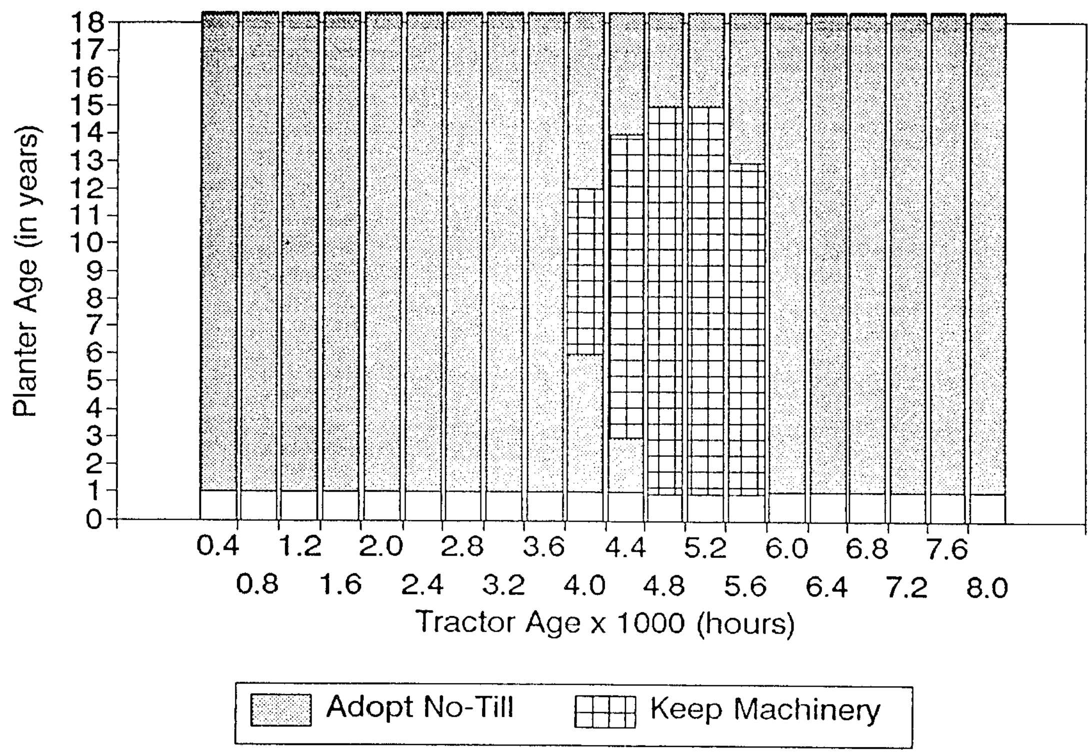


Figure 6.10

Optimal Policies for Slight Risk Aversion, a 3% Discount Rate, Estimated Yields, and Price State 1.

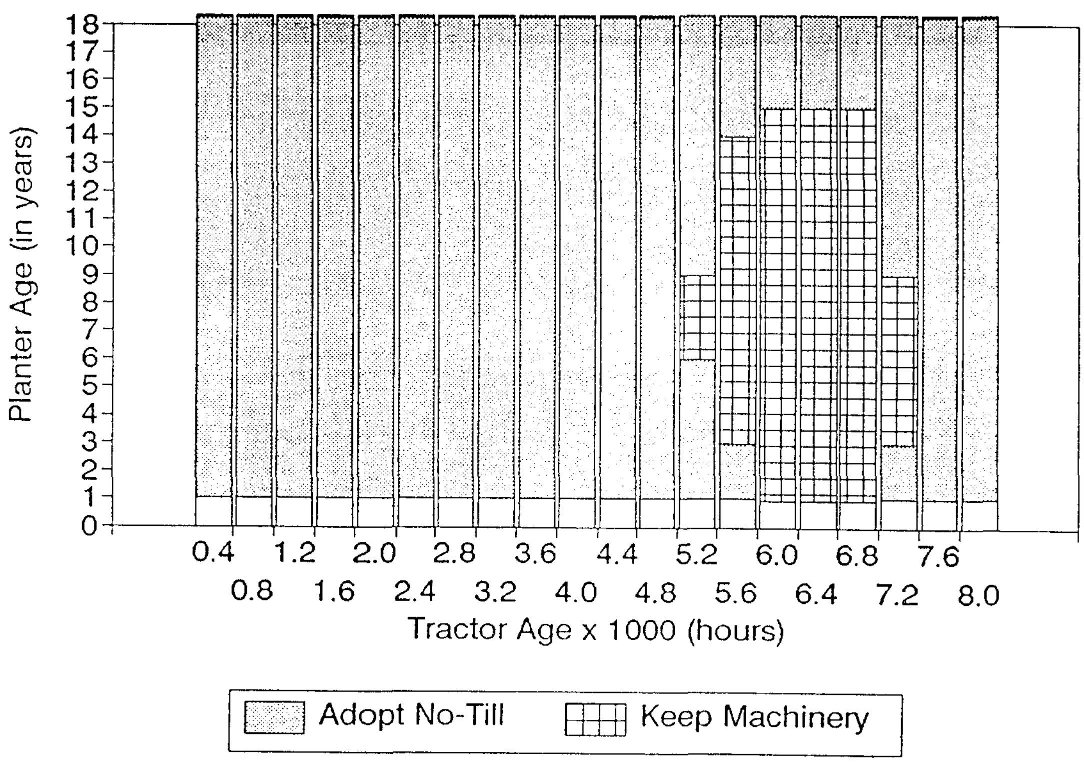


Figure 6.11

Optimal Policies for Slight Risk Aversion, a 3% Discount Rate, Estimated Yields, and Price State 3.

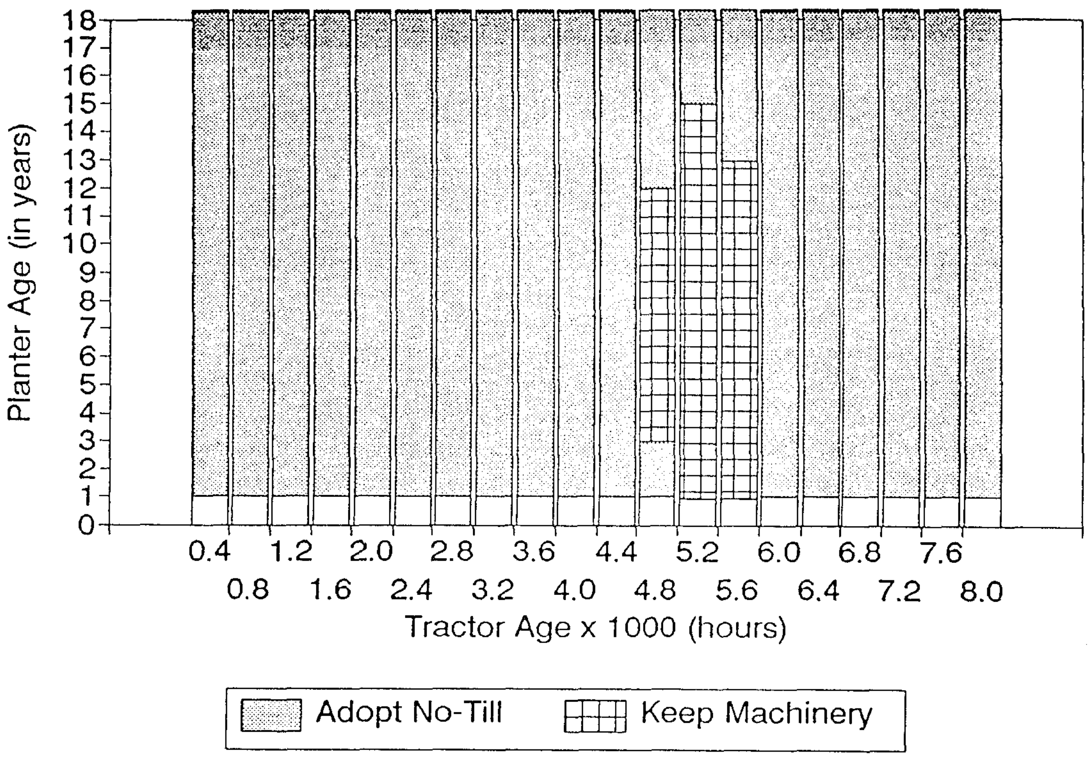


Figure 6.12

Optimal Policies for Moderate Risk Aversion, Median Prices, a 6% Discount Rate, Estimated Yields, and Price State 1.

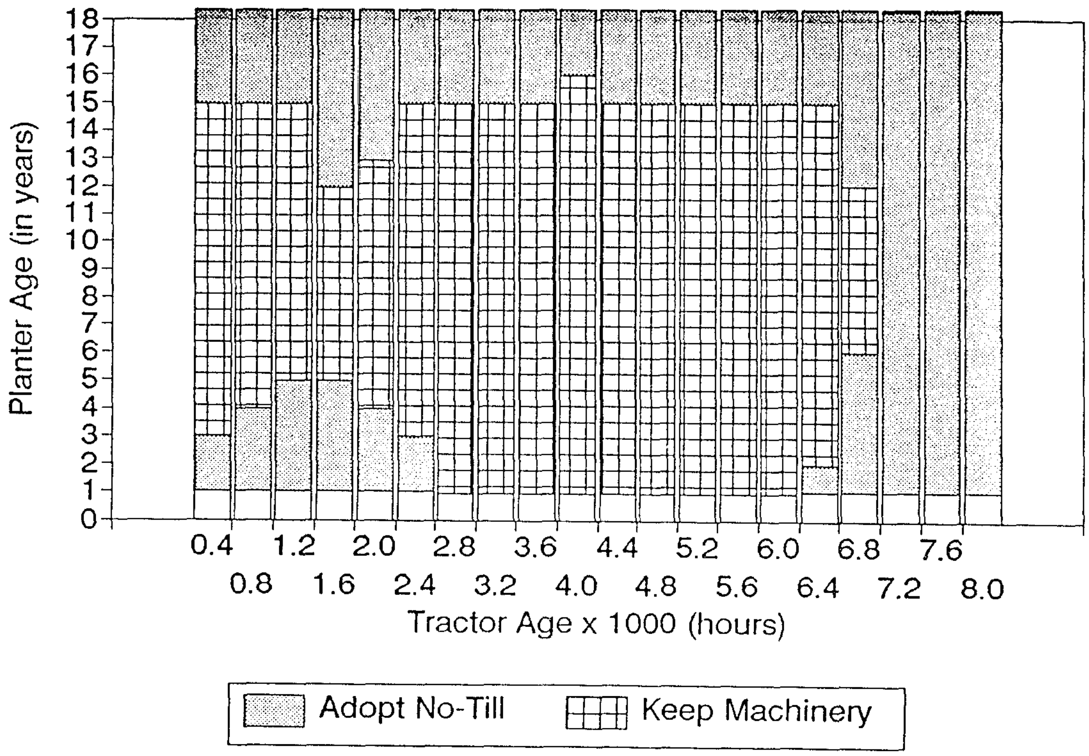


Figure 6.13

Optimal Policies for Moderate Risk Aversion, Median Prices, a 6% Discount Rate, Estimated Yields, and Price State 3.

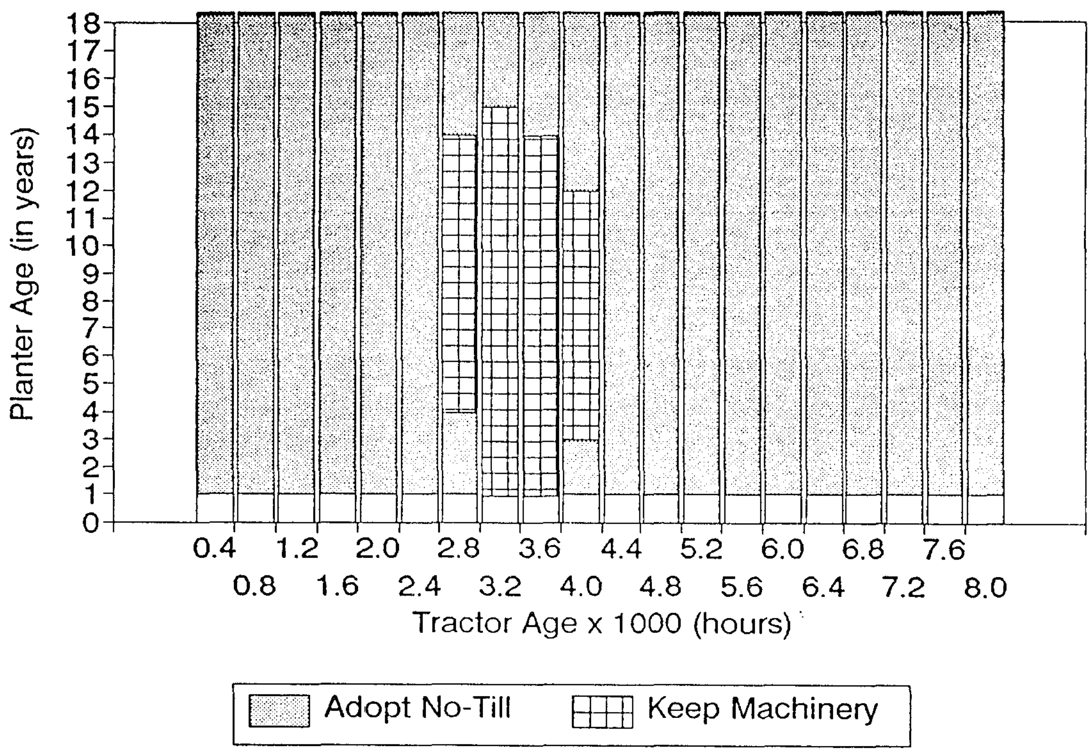


Figure 6.14

Optimal Policies for Slight Risk Aversion, Median Prices, a 6% Discount Rate, Estimated Yields, and Price State 1.

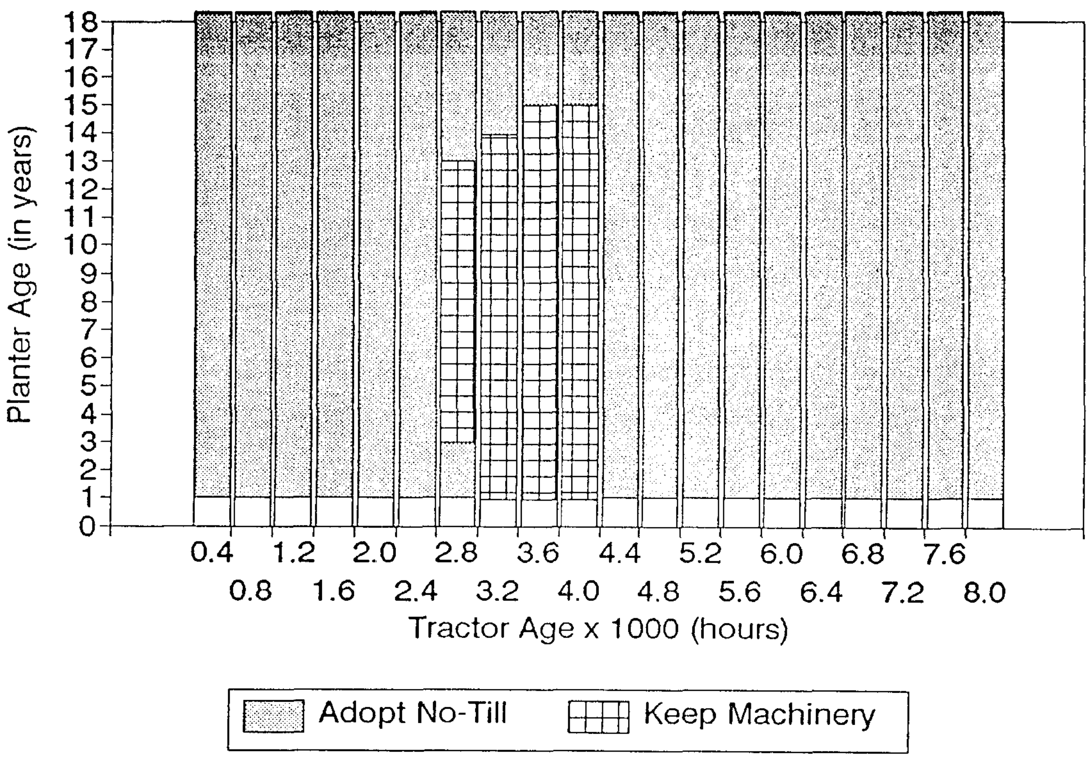
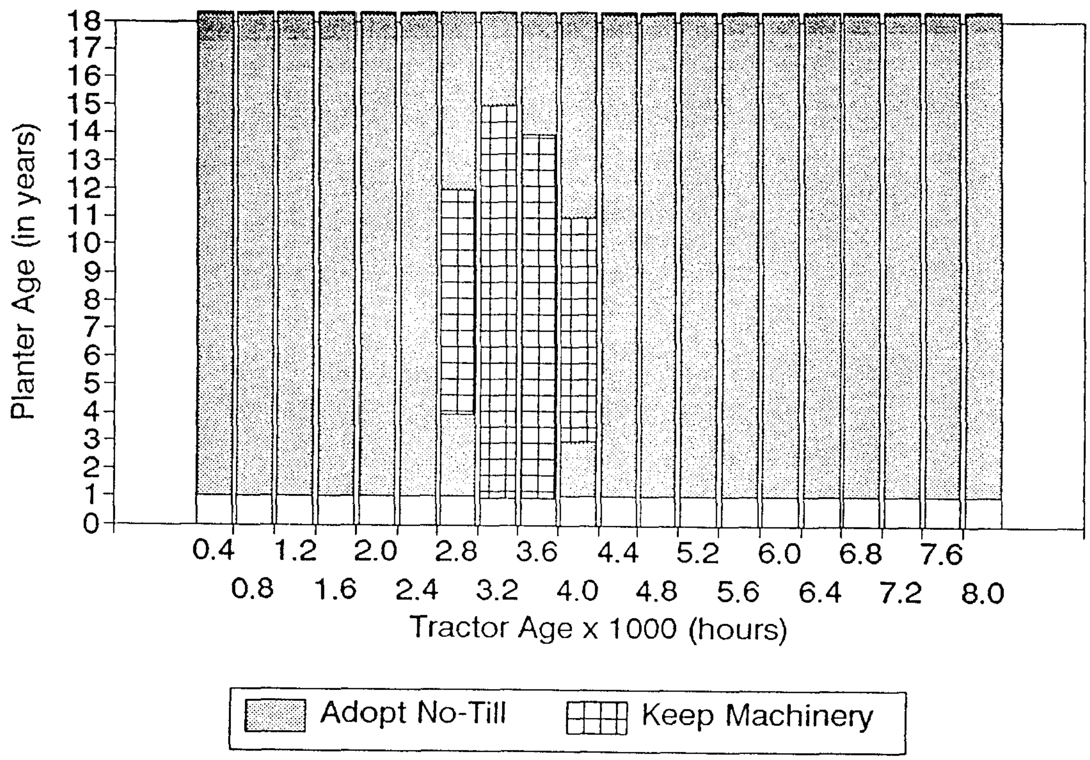


Figure 6.15

Optimal Policies for Slight Risk Aversion, Median Prices, a 6% Discount Rate, Estimated Yields, and Price State 3.



Two contrasts between the deterministic results and the risk-averse, stochastic results are remarkable. First, the profit-maximizing farmer always adopts the no-till technology in the first year under historical median or mean prices with limited renting options. The risk-averse, expected utility-maximizing farmer often waits until the initial machinery is worn out before adopting the no-till technology, although results vary according to the current price state.

Secondly, the cases in which the profit-maximizing farmer keeps the current machinery all include relatively low tractor ages. Indeed, the tractor age appears to be far more important than the planter age in determining the optimal time of adoption for the profit-maximizing farmer. However, for the risk-averse, expected utility-maximizing farmer, the current planter and tractor are more often kept when they are middle-aged than when very new, and the planter age is very important. The reason for this difference appears to be that the risk-averse farmer is much more influenced by declining trade-in values than is the profit-maximizing farmer. Although it is not a very realistic assumption, in this model the trade-in value is certain, as well as being very substantial. Therefore, the risk-averse, expected utility-maximizing farmer is anxious to capture as much of this large, certain value as possible, rather than use new equipment to produce highly uncertain net revenue from crop production.

Another simplistic assumption that contributes to the preference by risk-averse, expected utility-maximizing farmers to keep aging equipment is that machinery reliability is ignored in the model. If the model assumed more variable crop yields or crop production costs for aging equipment than for new equipment, risk-averse, expected utility-maximizing farmers would have less tendency to keep aging equipment.

Limited Renting Options and Equal Crop Yields

The effect of risk-aversion on optimal adoption strategies for the expected utility-maximizing farmer is even more severe when the long-run average yields for conventional tillage and no-till are expected to be equal[4]. If a 20% learning curve is expected, no-till adoption does not occur in any case. If a 10% learning curve is expected, no-till adoption usually occurs when the tractor age reaches 8,800 hours for price state 1, 7,600 hours for price state 3, 6,000 hours for price states 2 and 4, about 5,200 hours for price states 5 and 6, and 3,600 hours for price state 7 (Table 6.7). When no learning curve is expected, no-till adoption by the expected utility-maximizing farmer begins to occur when the tractor has accumulated about 1600 to 2800 less hours than for the 10% learning curve, or earlier if the planter is either very new or very old (Table 6.7).

Multiple Renting Options

When either the estimated crop yields or equal crop yields and a 20% learning curve are expected, the risk-averse, expected-utility maximizing farmer prefers to rent a no-till planter on 60 acres,

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[4] The long-run average yields were set equal to each other by multiplying all crop yields for the conventional tillage system by the ratio of the no-till mean yield divided by the moldboard plow mean yield.

Table 6.7 Conditions for which the Optimal Risk-Averse Policy* is to Adopt No-Till, Assuming Equal Yields and Limited Renting Options.

10% Learning Curve**

Initial Ages: Planter (years)	Initial Ages: Tractor (hours)	Initial Price State***
17	2000-3600	1
16-17	6800-8400	1
1-17	8800-max.	1
1-17	6000-max.	2
17	1600-2400	3
13-17	7200	3
1-17	7600-max.	3
1-17	6000-max.	4
1-17	5600-max.	5
1-17	5200-max.	6
1-17	3600-max.	7

No Learning Curve**

Initial Ages: Planter (years)	Initial Ages: Tractor (hours)	Initial Price State***
16-17	400-4400	1
17	4800-5600	1
16-17	6000-8000	1
1-17	8400-max.	1
16-17	400	2
17	800	2

No Learning Curve**

Initial Ages: Planter (years)	Initial Ages: Tractor (hours)	Initial Price State***
16-17	2000-2400	2
15-17	2800	2
14-17	3200	2
13-17	3600	2
1-17	4000-max.	2
16-17	400-3200	3
17	3600-4000	3
16-17	4400-6400	3
14-17	6800	3
1-17	7200-max.	3
16-17	400-800	4
17	1200	4
16-17	2000-2800	4
15-17	3200	4
14-17	3600	4
12-17	4000	4
1-17	4400-max.	4
14-17	2000	5
13-17	2400	5
1-2,9-17	2800	5
1-17	3200-max.	5
13-17	2000	6
11-17	2400	6
1-17	2800-max.	6
1-17	1200-max.	7

* Low risk aversion, defined as having a CPRRA coefficient equal to 0.5, is assumed (CPRRA is explained in Chapter 3).

** The 10% learning curve raises herbicide, fuel and oil, and labor costs for the no-till system by 10% in the first year, 7% in the second year, and 3.5% in the third year of using no-till. For no learning curve, these costs are not affected by experience.

*** Price State 1: $2.18 Corn and $5.63 Soybeans in previous year.
Price State 2: $2.18 Corn and $6.65 Soybeans in previous year.
Price State 3: $2.62 Corn and $5.63 Soybeans in previous year.
Price State 4: $2.62 Corn and $6.65 Soybeans in previous year.
Price State 5: $2.62 Corn and $10.08 Soybeans in previous year.
Price State 6: $3.59 Corn and $6.65 Soybeans in previous year.
Price State 7: $3.59 Corn and $10.08 Soybeans in previous year.

regardless of price state or age of machinery unless the conventional planter is at least 16 years old. If the conventional planter must be replaced, the optimal strategy depends on the tractor age, price state, and crop yield expectations. Considering the reluctance of the risk-averse, expected utility-maximizing farmer to adopt no-till when a 20% learning curve is expected, the opportunity to rent a no-till planter on a limited acreage and reduce learning costs may greatly accelerate adoption. Indeed, if equal mean yields for no-till and conventional tillage are expected, a comparison of the expected utility-maximizing farmer's optimal strategies for different learning curves indicates that this farmer will not adopt no-till at all unless a planter can be rented for a limited acreage or learning costs are small.

Differences between Optimal and Second-Best Policies

The profit-maximizing farmer and the expected utility-maximizing farmer often choose to keep existing machinery rather than purchase a no-till planter. However, when this occurs, the difference between the value functions for these two alternatives is usually small. For example, when the age of the tractor is 1,600 hours, the age of the conventional planter is less than 16 years, equal yields are expected for the the alternative tillage systems, and a 20% learning curve is expected, the profit-maximizing farmer chooses to keep these machines. However, the discounted net revenues for buying a no-till planter and 85 HP tractor are only $1,000 to $2,500 less than those for keeping the current machinery (Figure 6.16). When the moderately risk-averse farmer chooses to keep a 1,600 hour tractor and conventional planter rather than purchase a no-till planter (under price state 1 with a 6% discount rate), the difference in expected utility for these two choices exhibits a similar curve for different planter ages (Figure 6.17). One distinction between Figures 6.16 and 6.17 is that the risk-averse farmer is more inclined than the profit-maximizing farmer to purchase the no-till planter when the conventional planter is less than 8 years old. Another distinction is that there appears to be no meaningful way to measure the differences for the 30-year discounted sum of a CPRRA expected utility function in monetary terms.

Review of the Research Hypotheses

Five research hypotheses were proposed in Chapter 1. Although no formal criteria for acceptance or rejection of the hypotheses were proposed, the results of this chapter mostly support those hypotheses.

The first hypothesis was that the profit-maximizing farmer and expected utility-maximizing farmer would adopt the no-till system, but the timing of this adoption would depend on the age of the currently-owned machinery, the magnitude of learning curves, and whether opportunities to rent the no-till planter on a limited acreage exist. The profit-maximizing farmer always does adopt the no-till system within the range of parameters tested. Based on the estimated yields for corn and soybeans under the alternative tillage systems, the timing of adoption by the profit-maximizing farmer is not sensitive to age of the currently-owned machinery or the magnitude of learning curves. However, based on equal yields for the alternative tillage systems, the timing of adoption is sensitive to both of these variables. Small-scale renting

Figure 6.16 Penalty for Adoption with Various Planter Ages, a 1600 Hr. Tractor, and Profit-Maximization.

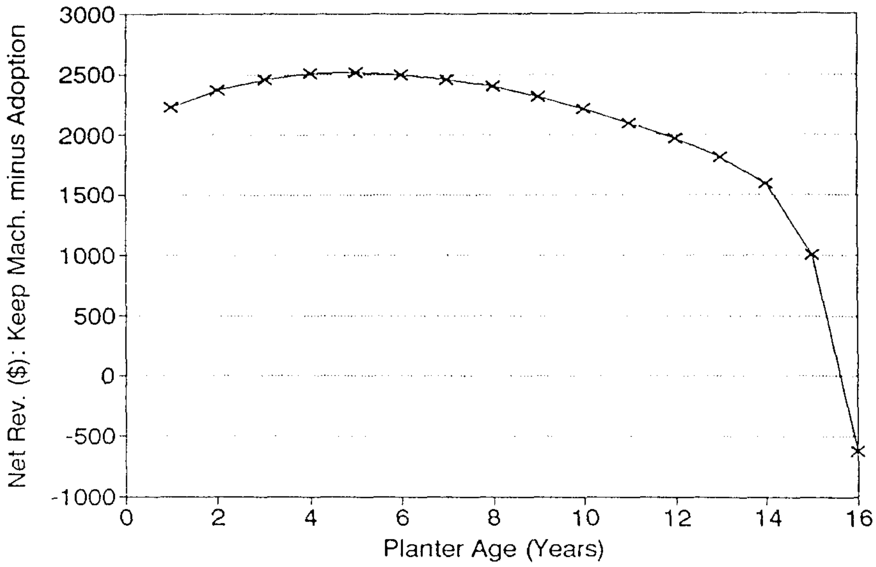
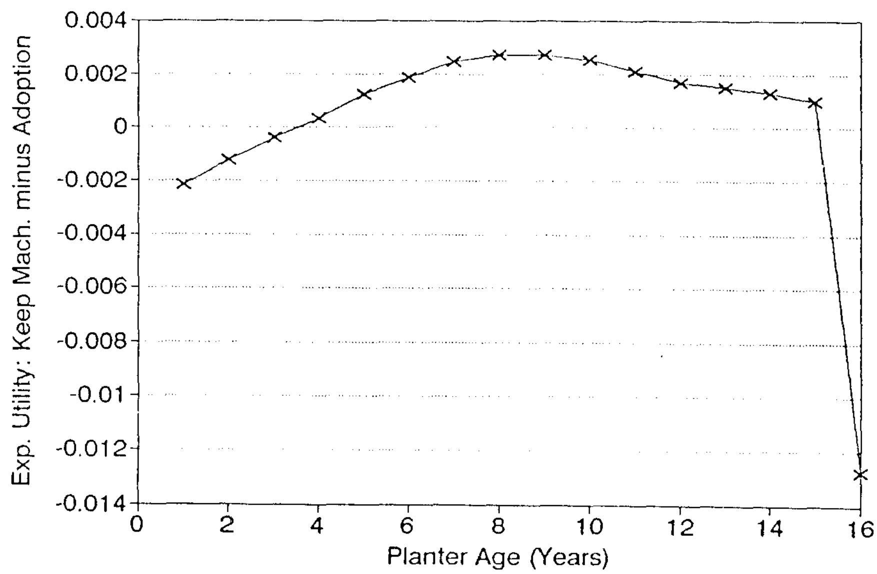


Figure 6.17 Penalty for Adoption with Various Planter Ages, a 1600 Hr. Tractor, and Exp. Utility Maximization.



opportunities sometimes advance and sometimes retard full-scale adoption of the no-till technology.

The expected utility-maximizing farmer always adopts the no-till system within the range of parameters tested if the analysis is based on the estimated corn and soybean yields. The timing of this adoption is sensitive to machinery age, learning curve magnitude, and planter rental possibilities. However, based on equal mean corn and soybean yields for no-till and conventional tillage, the expected utility-maximizing farmer will not adopt no-till unless there is less than a 20% learning curve or opportunities exist to rent the no-till planter on limited acreage. With some qualification, the first hypothesis therefore is confirmed.

The second hypothesis was that the profit-maximizing farmer and expected utility-maximizing farmer would more often adopt the no-till when their current machinery is old than when it is relatively new. The profit-maximizing adoption strategies support this hypothesis when equal crop yields for the two tillage systems are expected. The expected utility-maximizing adoption strategies support this hypothesis if the planter is at least 8 years old or the tractor is at least 6,000 hours old. When either the planter or tractor is very new, the optimal risk-averse strategy often is to trade-in the current equipment. However, as stated above, this result appears to be largely caused by an unrealistic assumption that trade-in values are known with certainty. The second hypothesis is generally confirmed, but with some exceptions for the risk-averse farmer when machinery is very new.

The third hypothesis was that a large learning curve effect would make no-till adoption less likely than would a small learning curve effect. Provided that the optimal adoption strategy was not to adopt the no-till system immediately for any learning curve, the optimal adoption strategies for the profit-maximizing and expected utility-maximizing farmers strongly supported this hypothesis.

The fourth hypothesis was that risk aversion and higher magnitudes of risk aversion would make no-till adoption less likely. The risk-averse, expected utility-maximizing farmer did adopt the no-till system for a much smaller range of planter and tractor ages than did the profit-maximizing farmer. Furthermore, the moderate level of risk aversion (constant partial relative risk aversion coefficient equal to 1.0) led to no-till adoption in many fewer cases than slight risk aversion (constant partial relative risk aversion coefficient equal to 0.5). The results of this chapter strongly support this hypothesis.

Finally, the fifth hypothesis was that both the profit-maximizing farmer and the expected utility-maximizing farmer would rent a no-till planter on a limited acreage if given this opportunity. Provided that a 20% learning curve is expected and the machinery ages are not so high that replacement becomes more attractive than renting, the results for multiple renting options support this hypothesis. Furthermore, as suggested in the hypothesis, renting the no-till planter on a limited acreage is rarely the optimal adoption strategy if little or no learning curve is expected. Thus, the implication that the no-till planter is rented on a limited acreage in order to reduce learning costs also is supported.

Chapter 7

SUMMARY AND CONCLUSIONS

Summary

This study has examined the effect of machinery replacement, learning curves, rental options, and risk aversion on optimal adoption strategies for the no-till system of conservation tillage. Expected profit-maximizing strategies and expected utility-maximizing strategies for a farmer in southwest Michigan with 400 acres of corn and 200 acres of soybeans are determined for various cases of machinery age, crop price expectations, crop yield expectations, learning curves, and available renting options. A range of discount rates and risk preferences are also examined in order to determine their effects. The results are informative not only to the promoters of conservation tillage, but also to anyone interested in rates of adoption for agricultural technology that is partly embodied in durable machinery.

Many economists and rural sociologists have tried to explain lags in the adoption of new agricultural technologies that appear to be very profitable in budget analyses. Starting with Griliches (1957), economists have documented that adoption lags are shortened as the relative profitability of the new technology increases, but have been less successful in explaining why this happens. Many economists explain adoption lags with Bayesian learning models, but have been unable to find strong empirical support. Although farm machinery accounts for a major share of production costs and is a major source of financial risk for U.S. farmers, only a few economists have examined the possible role of machinery investment and replacement decisions in causing adoption lags. Epplin et al. (1982) and Smith and Hallam (1990) found that it often is more profitable for farmers to wear out their existing machinery before replacing it with the machinery needed to practice conservation tillage than to purchase the conservation tillage machinery immediately.

The no-till system of conservation tillage is a good example of a technology that is largely embodied in durable machinery and has been adopted much more slowly that its promoters had hoped. No-till technology is promoted both because it reduces soil erosion and because it can reduce fuel, labor, and machinery requirements and their associated costs. However, no-till generally requires more herbicide than conventional tillage, and herbicide cost increases often offset reductions for labor costs, machinery operating costs, and machinery fixed costs. Moreover, in northern states such as Michigan, the tendency of no-till to retard the warming of the soil in the spring sometimes reduces crop yields. Therefore, it has not been clear or certain that the no-till system is much more profitable even in the long run than conventional tillage. In such a case, adjustment problems associated with adopting a new technology, often described as a learning curve, may discourage adoption. Also, in a case where the long-run advantage of the new technology is small, the costs of purchasing new equipment and the relatively low trade-in value of used equipment may discourage or at least delay adoption. The primary objective of this study has been to determine to what extent these factors would cause expected profit-maximizing and risk averse, expected utility-maximizing farmers to delay adoption of the no-till technology.

The analysis of optimal adoption strategies is based on the economic theory of optimal replacement, adjustment costs, and response to risk by risk-averse decision makers. In order to consider the possible replacement of machinery with new machinery that is not identical, adjustment costs, and risk-aversion in the machinery replacement problem, a dynamic optimization technique is required. The method of dynamic programming was chosen because it allows all of these variables to be considered in numerical optimization problems with long planning horizons. Bellman's principle of optimality allows the optimization problem to be solved one period at a time, working backwards from the end of the planning horizon to the beginning.

The objective function for the deterministic dynamic programming model is the minimization of expected net cost over the planning horizon. The state variables are the planter age, tractor age, years of experience with the no-till technology, and which machines are owned. The control variables are binary choices among various machinery purchase, rental, and technology selection options. The options include a choice between a no-till planter and a conventional planter and a choice between a 140 HP tractor and an 85 HP tractor. The larger tractor is capable of implementing either the conventional tillage or no-till technology. The smaller tractor is only capable of implementing the no-till technology, but has a much lower purchase price and lower repair costs than the larger tractor. The planters may be either purchased or rented. Variable input levels are assumed to be fixed by the choice of tillage technology.

The objective function for the stochastic dynamic programming model is the maximization of an expected utility function. The specific function chosen exhibits constant partial relative risk aversion (CPRRA). The degree of risk-aversion is determined by the risk-aversion parameter. The effects of risk aversion parameters of 1, 0.5, and 0 (risk-neutrality) were examined. Control variables and all but one state variable are the same as for the deterministic model. The additional state variable is the previous period's combination of prices for corn and soybeans. The probability of that any price state would occur in the current period was set according to which price state occurred in the previous period, reflecting the strong serial correlation exhibited by Michigan annual corn and soybean price data.

Crop yields were estimated for both the deterministic and stochastic dynamic programming models using modified versions of the CERES-MAIZE and SOYGRO crop growth simulation models. Simulated yields were used instead of actual experimental yields because no tillage experiments have been conducted for long periods of time with similar soils and climate. Experimental yields also do not show planting date effects that can strongly affect the relative crop yields for no-till and conventional tillage. The CERES-MAIZE and SOYGRO models were modified to account for the effects of surface crop residue on corn and soybean growth, primarily by reducing soil evaporation and by making the models more sensitive to reduced soil temperature. Corn and soybean yields were then estimated using 33 years of historical climate data and soil parameters for an Oshtemo sandy loam. Planting dates were determined in two steps: (1) by modifying CERES-MAIZE to determine days suitable for fieldwork based on daily soil moisture and temperature criteria; and (2) by calculating how many of these "good field days" would be required for pre-plant tillage, planting, and nitrogen fertilizer application on the 400 acres of corn and 200 acres of soybeans.

The estimated mean corn and soybean yields for the 33 years of climatic data and Oshtemo sandy loam were very slightly higher for the no-till system than for conventional tillage. However, given the magnitude of year-to-year variation in crop yields for both tillage systems, only the differences in mean soybean yields between the alternative tillage systems were statistically significant (for 2 of 3 fall plowing scenarios). Also, variation in corn yields across planting dates is often very high. These results are consistent with agronomic studies conducted on similar soils in the same general location as assumed for the estimation of corn and soybean yields (Bronson, 1988; Hesterman et al., 1988). The crop yield results also illustrate the fallacy of making long-run comparisons by extrapolating from only a few years of data.

One surprising result is that the estimated mean crop yields for different levels of fall plowing completion were essentially equal, although the variance of crop yields increased as more plowing had to be completed in the spring. Part of the explanation is that there usually were enough good field days to complete corn planting in a timely manner if corn planting is given priority over pre-plant tillage for soybeans. This sometimes delays soybean planting greatly, but soybeans appear to be much less affected by planting date than is corn. Another part of the explanation is that the SOYGRO model does not appear to be sufficiently sensitive to cold fall temperatures, but correcting this deficiency was beyond the scope of this analysis.

Based on mean crop yields and either the historical median crop prices or current crop prices, revenues net of variable costs are only slightly higher for the no-till system than for conventional tillage. The difference in revenues net of variable costs between the alternative tillage systems is particularly small when the relatively low, current prices are assumed because the no-till system has higher variable costs than the conventional tillage system. However, when the historical median prices are assumed and crop yields for all planting dates are considered, revenues net of variable costs for no-till come very close to exhibiting second-degree stochastic dominance over revenues net of variable costs for conventional tillage. If possible savings in machinery fixed costs for the no-till system are considered, revenues net of variable costs for the no-till system would exhibit second-degree stochastic dominance over revenues net of variable costs for the conventional tillage system. This implies that in the long-run, the no-till system is not only more profitable than the conventional tillage system, but it also would be preferred by all risk-averse farmers.

Results for the deterministic dynamic programming model indicate that the optimal adoption strategy for the profit-maximizing farmer is to replace the conventional planter with a no-till planter and the 140 HP tractor with an 85 HP tractor very quickly, if not immediately. Based on the estimated mean corn and soybean yields, different expected crop prices and learning curve magnitudes have no effect on the optimal adoption strategies for the profit-maximizing farmer. Raising the discount rate to 9% delays adoption by the profit-maximizing farmer for one year if the tractor is almost new and the 20% learning curve is assumed.

However, when crop yields are expected to be equal for the alternative tillage systems, the optimal adoption strategies frequently are to keep using current equipment several years before replacing it with the no-till planter and the 85 HP tractor. The longest lags before adoption of the no-till system occur when the initial machinery is only one or two years old. The optimal time of replacement is usually when the tractor reaches a critical age, which indicates that the optimal time of replacement is sensitive to increasing repair costs because tractor repair costs are much higher than planter repair costs. When equal crop yields are assumed, changes in the discount rate and learning curve do alter the optimal time of adoption significantly. Raising the discount rate from 3% to 6% or from 6% to 9% often delays the optimal time of adoption by a year or more.

When the possibility of renting a planter on 60, 120, or 240 acres exists and a 20% learning curve is expected, the profit-maximizing farmer often rents the no-till planter for one or two years on 60 acres before purchasing the no-till planter and changing tractors. However, based on the estimated crop yields, if the tractor has accumulated over 3,200 hours of use, or if a 10% learning curve or no learning curve are expected, the optimal policy for profit-maximizing farmers usually is to replace the conventional planter with the no-till planter and the 140 HP tractor with the 85 HP tractor immediately. Based on equal yields for the two tillage systems, the profit-maximizing farmer may wait until the tractor has accumulated up to 5,200 hours before purchasing the no-till planter. When additional renting options are considered, the profit-maximizing strategy is not much affected by crop price expectations.

The optimal adoption strategies are quite different for the risk-averse, expected utility-maximizing farmer than for the expected profit-maximizing farmer. The risk-averse, expected utility-maximizing farmer who expects a 20% learning curve usually does not adopt the no-till system until the tractor has accumulated at least 4,000 hours of use if either the previous corn or previous soybean price was less than the historical median prices. In contrast, the profit-maximizing farmer would adopt no-till immediately, even if the much lower 1991-92 prices are assumed for the entire planning horizon. If a 20% learning curve is expected and mean yields for no-till and conventional tillage are assumed to be equal, the profit-maximizing farmer will adopt the no-till system if the tractor has accumulated about 4,000 hours of use or the planter is more than 16 years old. The risk-averse, expected utility-maximizing farmer will not adopt no-till at all in this case unless he or she has the opportunity to reduce learning costs by renting a no-till planter on a limited acreage. Although the profit-maximizing farmer prefers the option of renting a no-till planter on a limited acreage in a few cases, the risk-averse, expected utility-maximizing farmer prefers renting on a limited acreage in every case.

Conclusions

Crop Yield Estimates for No-till and Conventional Tillage

Although crop yield estimates were only an intermediate result, they provided important lessons for future research regarding alternative crop production techniques. Many of these lessons appear to be already understood by agronomists, but have not yet been learned by most agricultural economists. From the economist's perspective, agronomists often appear to be overly cautious in interpreting the results of agronomic experiments. Statistical analysis by agronomists usually stops with the analysis of variance (ANOVA), and the qualitative conclusion that crop yields for one treatment are higher than for other treatments. Economists often complain that "higher yield" cannot be used in a budget to determine relative profitability without first being quantified. Agronomists often respond to such complaints by saying that they do not yet have enough information to quantify the crop yield advantage.

The crop yield estimates obtained by the modified CERES-MAIZE and SOYGRO crop growth simulation models illustrate the need for caution when interpreting results from agronomic trials. At least on a sandy loam soil in Michigan, relative crop yields for the no-till and conventional tillage system appear to vary greatly according to weather conditions and planting date. The simulation models may possibly exaggerate some of this variation, but the variation in the estimated yields is very consistent with levels of variation reported in agronomic journals and theses. The amount of variation in relative crop yields from year to year implies that results of economic analyses that are based on mean yields from one, two, or three years of agronomic trial data should be regarded as very tentative at best.

The amount of variation in estimated corn yields across planting dates also indicates that planting dates deserve more attention in agronomic trials. Conclusions regarding relative crop yields for alternative technologies that are based on results for single planting dates will often change if a different planting date is selected. Thus, obtaining crop yield results for a range of planting dates is highly desirable. However, this recommendation would be very expensive to implement in actual trials. A good alternative to conducting agronomic trials with several planting dates would be to collect the data needed to calibrate the appropriate crop growth simulation model for each treatment in the agronomic trial and then estimate crop yields for additional planting dates using that model.

The methodology used to determine operation dates and estimate crop yields based on weather data, soil data, and machinery/labor resources appears to be a very feasible way to predict how different crop production technologies will perform on individual farms. Agronomic trial data are available for only a few soils and locations in Michigan or other states. Since the performance of many crop production technologies is sensitive to local soil and weather conditions, agronomic trial data provide an incomplete and sometimes misleading picture of how the technology will perform on farms with different soil and weather conditions. In contrast, the soil and weather data needed to run the crop growth simulation models and the model that determines good field days are available for dozens of soils and locations in Michigan[1]. The crop growth simulation models also can indicate how a specific technology will perform over the full range of planting dates that farms with limited machinery/labor resources may face.

However, the crop growth simulation models must be validated by comparing simulation results with agronomic trial data for different production technologies before the simulation results can be considered reliable. For some technologies, modifications must be made to the simulation models in order to capture the full effects of those technologies on crop growth and yield. Such modifications were made in this analysis in order to include the effects of surface crop residue on corn and soybean growth and yield. Other effects of reduced tillage on corn and soybean growth and yield[2] have been documented in agronomic journals and could be added to the CERES-MAIZE and SOYGRO models through further modifications. Yet it is difficult to validate even the current CERES-MAIZE and SOYGRO models because the necessary data are rarely collected in agronomic trials. The biggest obstacle to predicting the performance of different technologies on individual farms using the crop growth simulation models is the current scarcity of validation data.

The other important deficiency of the methodology used to determine operation dates and estimate crop yields for alternative tillage systems is that it is currently very time-consuming. Much time

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[1] Some of the CERES-MAIZE and SOYGRO data inputs must be estimated for many soils and locations from other data using procedures described by Ritchie et al. (1990). However, the IBSNAT project (Chapter 4) is assembling input data files for CERES-MAIZE and SOYGRO for soils and locations all over the U.S. and the world.

[2] Some of these additional effects are listed in Chapter 4.

could be saved by writing a computer program which would: (1) determine operation dates from weather data, soil data, and a description of available machinery and labor constraints; (2) write these dates into the input files for CERES-MAIZE and SOYGRO; (3) run the CERES-MAIZE and SOYGRO models for all operation dates; and (4) report summary statistics of the yield results across all operation dates. Once a computer program is developed that automates these tasks, the only time-consuming task would be specifying the input files, calibration, and validation of the models for the different technologies.

Economic Analyses of No-Till Adoption

The contrast of results for static economic analyses of whether to adopt the no-till system and dynamic economic analyses of when and how to adopt this technology suggest that the no-till adoption process can only be understood through dynamic analyses. The budget analysis indicates that profit-maximizing farmers should adopt the no-till system, although adoption increases profits very little unless possible savings in machinery fixed costs are considered. The stochastic dominance analysis indicates that all risk-averse, expected utility-maximizing farmers should prefer the no-till system if they consider the possible savings in machinery fixed costs. Yet the static economic analyses only indicate that profit-maximizing and expected utility-maximizing farmers should adopt no-till in the long-run. The static analyses cannot answer the question of whether there are any reasons why profit-maximizing and expected utility-maximizing farmers would wait a number of years before adopting the no-till system. The static analyses also cannot answer the question of whether the adjustment costs for adopting the no-till technology are so great that profit-maximizing farmers or risk-averse, expected utility-maximizing farmers would not adopt the no-till system at all.

The deterministic dynamic programming analysis clearly indicates that the profit-maximizing farmer should adopt the no-till system after little or no delay. However, the deterministic dynamic programming analysis also indicates that the profit-maximizing strategies are sensitive to very small differences in expected crop yields. Particularly when equal yields are expected, the optimal adoption strategies for profit-maximizing farmers also are sensitive to learning curves and crop price expectations. The conclusion suggested by the deterministic dynamic programming analysis is that dynamic adjustment costs will not delay adoption of the no-till system by profit-maximizing farmers when no-till is much more profitable in the long run than conventional tillage, but will delay their adoption of no-till if the long-run profit advantage is small.

The results of the stochastic dynamic programming analysis of optimal adoption strategies for risk-averse, expected utility-maximizing farmers are strikingly different than for the previous three economic analyses. If last year's soybean prices were low (price states 1 and 3), the optimal adoption strategy often is to wait until the conventional planter is at least 15 years old and the 140 HP tractor has accumulated at least 6,400 hours of use before adopting the no-till system. A higher degree of risk aversion increases the range of planter and tractor ages for which the optimal strategy is to keep using the conventional planter and 140 HP tractor. Furthermore, if equal crop yields for the alternative tillage systems and a 20% learning curve are expected, the optimal strategy for risk-averse farmers is never to adopt no-till at all unless there are opportunities to reduce the costs of learning by renting a no-till planter on a limited acreage.

One of the objectives of this study was to assess the effect of machinery rental policies by Soil Conservation Service (SCS) districts and machinery dealers on the timing of no-till adoption by the profit-maximizing and the risk-averse, expected utility-maximizing farmers. The dynamic programming results indicate that the profit-maximizing farmer will take advantage of opportunities to reduce learning costs by renting a no-till planter on a limited acreage provided that: (1) a substantial (i.e. 20%) learning curve is expected; and (2) currently-owned machinery has not accumulated much use. If a less severe learning curve is expected or if the current machinery has already been used several years, the profit-maximizing farmer will ignore renting possibilities and purchase a no-till planter and smaller tractor without delay. If the profit-maximizing farmer does rent a no-till planter, it is only for one or two years. Making no-till planters available for rental on a limited acreage actually delays full-scale adoption by the profit-maximizing farmer in some cases. It appears that the primary benefit of providing profit-maximizing farmers with the possibility of renting a no-till planter on a limited acreage would be to demonstrate the long-term profitability of no-till technology on their farm (which was assumed in the dynamic programming analysis). The opportunity to reduce learning costs by renting a no-till planter on a limited acreage appears to be of secondary importance to the profit-maximizing farmer.

However, the possibility of reducing learning curve costs by renting a no-till planter appears to have great importance to the risk-averse, expected utility-maximizing farmer. If this farmer expects a 20% learning curve, he or she does not adopt the no-till technology until either the crop prices they expect for the current period are quite high (as in price state 7), or the current machinery is well used. If, in addition, long-term average crop yields are expected to be equal under the two tillage systems, he or she will not adopt no-till at all unless less than a 20% learning curve is expected. However, the risk-averse, expected utility-maximizing farmer will rent a no-till planter on a limited acreage immediately, thereby reducing the learning costs. The reduction in learning costs will often accelerate full-scale adoption (depending on current machinery age and price expectations), or make the difference between adoption and non-adoption. Given that most farmers appear to be at least somewhat risk-averse (Lins et al., 1981; Alderfer, 1990), offering no-till planters for rental on limited acreage therefore seems to be an essential component of any program to encourage no-till adoption.

The results of the stochastic dynamic programming analysis suggest that adoption of no-till technology can be accelerated in three ways: (1) demonstrating a long-run crop yield advantage for no-till on a variety of different soils; (2) providing farmers with greater technical support during the initial years of adoption to reduce learning curve costs; and (3) increasing the availability of no-till planters for rental on limited-acreage. At least over the range of parameters tested, the most important of these three mechanisms appears to be the demonstration of a long-term crop yield advantage for the no-till technology. Even the profit-maximizing farmer with no risk aversion was found to delay adoption of no-till when he or she did not expect that it provides higher crop yields than conventional tillage. The risk-averse, expected utility-maximizing farmer was often found not to adopt the no-till system at all when he or she did not expect higher crop yields for the no-till system than for conventional tillage. Obviously, if a long-term yield advantage does not exist then trying to demonstrate one is probably futile. But it appears that no-till does provide higher yields than conventional tillage on many soils[3]. Nevertheless, these higher yields need to be demonstrated in many locations on a scale that convinces farmers that they can obtain similar results on their farms.

Alternatively, if it can be demonstrated to groups of profit-maximizing or expected utility-maximizing farmers that variable costs for the no-till system are less than or equal to those of conventional tillage, this would have similar effects to demonstrating a crop yield advantage. Designing and demonstrating weed control strategies for no-till crop production that achieve the same level of weed control as for conventional tillage without increasing herbicide cost would have this effect, if it is possible. Farmers with unusually high labor costs also may find that the no-till system has variable costs that are less than or equal to those of conventional tillage.

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[3] Based on the yield estimates of this study and some of the agronomic studies cited in Chapter 4.

The other two mechanisms for accelerating the adoption of no-till technology work together. Technical support in the initial implementation of no-till would reduce learning costs. Renting a no-till planter on a limited acreage rather than trying to immediately implement no-till on all crop acres also would reduce learning costs. Furthermore, if technical support can greatly reduce learning costs then profit-maximizing and expected utility-maximizing farmers usually would not prefer to rent the no-till planter on a limited acreage. Technical support and short-term renting possibilities do exist and this study does not try to assess whether the supply meets the potential demand. Nevertheless, the relatively slow rate of no-till technology in Michigan compared to the rate of adoption for other agricultural technologies (e.g. hybrid seed, pesticides) and compared to the rate of no-till adoption in other midwestern states suggests that increased technical support and machinery renting availability may still have some effect.

Although this issue was not studied thoroughly, the cost of renting no-till planters appears to be less important than the availability of this option to all farmers when the planters are needed. The rental charges assumed in this study are at the upper end of those suggested by SCS agronomist Gerry Grigar (1992) and the NAEDA (1992). Rental on a limited acreage was often selected as a profit-maximizing or expected utility-maximizing strategy when the cost is higher than it often may be in practice. Therefore, reducing the cost of renting would increase the number of cases for which renting on a limited acreage would be an optimal strategy, but it does not appear that the increase would be large.

Technical support is provided by the SCS, the cooperative extension service (CES) of the land-grant universities, and other groups. Farm publications also occasionally provide useful information about conservation tillage practices. However, farm publications and extension publications do not address the individual farmer's unique problems and concerns. The human resources of the SCS and CES are limited, so they generally are not able to provide individualized technical help to a large proportion of farmers. Yet Peter Nowak, who has studied conservation tillage adoption extensively, argues (1983) that personal visits by conservation tillage specialists to new adopters are a necessary component of any successful promotion effort. One form of technical support that appears to work very well is to organize no-till clubs of farmers who meet regularly to share their experiences with adopting no-till technology (Berkland et al., 1983). The club members also share their experience of adapting no-till technology to their farms and to different soil and weather conditions.

Limitations of the Analyses

It is important to recognize that the results of the economic analyses and the conclusions that are drawn from them are based on parameters that will vary significantly from farm to farm. These parameters include acreage, the operating capacity (acres/hour) of the machinery set, purchase prices and trade-in values for the machinery, repair costs for the machinery, labor availability and cost, herbicide and insecticide costs, and fertilizer costs. Machinery trade-in values and repair costs are known to be especially variable, but also are very important in determining the optimal adoption strategies for profit-maximizing and expected utility-maximizing farmers. There often may be less of a difference between purchase prices for a conventional planter and a no-till planter or more of a difference in the two tractor prices than was assumed in this analysis. It also should be emphasized that the estimated crop yields used in the economic analyses are based on one relatively sandy soil and two nearby locations in southern Michigan.

Changes in any of the above parameters would probably alter the results at least slightly. Increasing the trade-in values or repair costs for machinery would tend to make no-till adoption more likely. If a farmer compares a 140 HP tractor with a cab to an 85 HP tractor without a cab, this would make no-till adoption more likely. On the other hand, if a heavier soil or higher purchase prices for new machinery were assumed, these factors would tend to make no-till adoption less likely than is indicated by these results.

Farmers' objectives often are more complex than expected profit-maximization or expected utility-maximization. The specific form of the expected utility function used in the stochastic analysis also has very weak empirical support (Chavas and Holt, 1990; Pope and Just, 1991). The constant relative risk aversion (CRRA) function that considers wealth in addition to income has stronger empirical support than the constant partial relative risk aversion (CPRRA) function used in this analysis, but it was not feasible to include wealth in the dynamic programming model. The $90,000 that had to be added to income in the expected utility calculations in order to use this expected utility function with a risk aversion coefficient less than or equal to one also serves to reduce the level of absolute risk aversion below levels estimated for many U.S. farmers (Lins et al., 1981; Alderfer, 1990). The model of price expectations used in the stochastic analysis is very crude, with only seven combinations of corn and soybean prices. Although the price state probabilities are consistent with the historical data, many farmers would probably suggest different probabilities. However the objective of the stochastic dynamic programming analysis was only to assess whether risk aversion has an important impact on the optimal adoption strategies when crop yield and price uncertainty are considered. The results of the stochastic dynamic programming model clearly satisfied this limited objective.

Sources of risk other than crop yield and price were ignored in the stochastic analysis. Examples include herbicide, fuel, and labor costs, repair costs, machinery reliability, availability of rental machinery, and machinery trade-in values. Since results for the stochastic dynamic programming model with risk aversion are sensitive to any variation in the model parameters, adding additional sources of risk would probably change the stochastic results at least slightly. However, it is not feasible to add any additional stochastic state variables and still solve the stochastic dynamic programming model using the current Microsoft FORTRAN compiler. If any other state variables are added, other state variables or levels of state variables would have to be removed. A larger stochastic model could be solved on a mainframe computer, but it would be quite expensive to do so unless the user is not charged for CPU time.

Additional ways to adopt no-till technology also were not considered in the dynamic programming analyses. Other methods of adoption include modifying a conventional planter to plant in surface residues by attaching coulters ahead of planter units and various machinery financing alternatives. It certainly is feasible to add modification of the conventional planter to the list of control options considered. The only difficulty caused by adding this option is that no-till planters usually are constructed with heavier steel and parts than conventional planters in order to withstand the additional stresses of planting in untilled soil. Modified conventional planters therefore are not considered to be as reliable as planters that are designed for no-till. However, machinery reliability was left out of the analysis in order to reduce stochastic variables and because there has been little empirical, public research concerning the frequency of planter breakdowns under different residue conditions. Yet planter modification would be a less costly adoption strategy than purchase of a new no-till planter, so if modified conventional planters are not much more prone to breakdowns than no-till planters this option might accelerate adoption by risk-averse, expected utility maximizing farmers.

Financing options are only relevant for the stochastic dynamic programming analysis or if taxes are considered because if the interest rate on borrowed capital exceeds the discount rate a profit-maximizing farmer will not borrow capital unless the after-tax interest rate is less than the discount rate. For most farmers the interest rate on agricultural loans probably does exceed their discount rate. Taxes were excluded from the analysis because it appeared difficult if not impossible to add enough state variables in the stochastic dynamic programming model to consider tax effects without making the dimensions of the model too large to solve with Microsoft FORTRAN. However, tax considerations and financing could be added to a mainframe version of the model. Also, tax considerations and financing options could be added to the Microsoft FORTRAN version if experience and learning curves were ignored or if crop prices were assumed to be independently distributed from one year to the next[4]. It would be useful to test whether financing options and tax considerations alter the optimal adoption strategies for risk-averse expected utility-maximizing farmers, so one or more of these approaches should be pursued in further research.

Suggestions for Further Research

There are a number of ways to increase the realism of the dynamic programming models used to determine optimal adoption strategies for the no-till technology. Several of these were mentioned above, including the addition of additional sources of risk, adding the possibility of modifying the conventional planter to plant in crop residue, and considering financing options and tax effects. Many economists will have sufficient computer resources to overcome the constraints that limited how many state variables and levels of state variables could be included in the model. The crude model of price variation that was used

[4] The option of assuming independence of price distributions from one year to the next reduces the number of state variables, thus computer memory requirements. However the time required to obtain a solution would increase in direct proportion to the number of state variables required to calculate tax deductions.

in the stochastic model also could be much refined. The modified CERES-MAIZE and SOYGRO models used to estimate crop yields also require thorough validation before the crop yield results used in the analysis of optimal adoption strategies can be considered reliable. All of these efforts would make the deterministic and stochastic dynamic programming models much better tools for predicting the effects of alternative public policies on the adoption of no-till technology.

The analysis here could easily be extended to other forms of conservation tillage, especially chisel plow and ridge-till systems. The change from moldboard plowing to chisel plowing involves fewer machinery decisions and less of a learning curve than the change to no-till. These differences between the adoption of no-till and chisel plow technology perhaps explain why adoption of chisel plow tillage systems has occurred far more quickly in Michigan than adoption of no-till. It would be interesting to test whether it is optimal for profit-maximizing and risk-averse, expected utility maximizing farmers to adopt chisel-plowing instead of no-till and what the optimal strategies are for adoption of chisel plow tillage systems.

The dynamic programming analysis also could be extended to transitions from conventional farming to organic farming or from irrigated crop production to dryland crop production in regions where groundwater resources are declining. In the case of organic farming, the emphasis would be on finding the optimal strategy for maintaining sufficient cash flow for family living expenses and debt service when learning curves are very important and several years of chemical-free farming may be required before organic certification and higher prices can be obtained. In the transition to dryland crop production, both machinery replacement and maintaining a sufficient cash flow for debt service and family living would be important.

In general, the optimal adoption strategies for the no-till technology demonstrate that when farmers are considering major changes in products and/or production technology that involve machinery or other production durables, a dynamic analysis of their choices provides very useful information to policy makers. Only a dynamic analysis is able to assess the effect of short-term transition strategies such as renting equipment on a limited acreage on farmers' decisions. Only a dynamic analysis is able to consider learning curve effects on farmers' decisions. Finally, a stochastic analysis is needed to consider the possible effects of risk aversion on farmers' decisions. Risk-aversion effects were shown in the analysis of no-till adoption strategies to be extremely important. Two general features of no-till adoption strategies are that they involve large expenditures for illiquid assets and highly variable returns. Farmers often face other decisions that share these two general features, so policy makers often will require analyses of farm choices that are both dynamic and stochastic.

Appendix A

PROOF OF THE OPTIMAL REPLACEMENT RULES

This appendix presents part of the derivation of the optimal rules for machinery replacement in Chapter 2. The derivation starts from the premise that if the best replacement policy is to replace equipment every n years, then the two inequalities:

$$K_{n+1} - K_n > 0 \quad \text{and} \quad K_{n-1} - K_n > 0$$

must hold, where K_n and K_{n+1} are the discounted values of all future costs associated with a policy of replacing equipment every n and n+1 years, respectively. It is shown here that $K_{n-1} - K_n > 0$ is equivalent to:

$$\frac{Cn}{1 - [1/(1+r)]} < K_{n-1}\text{, which is inequality (5) in Chapter 2,}$$

and that $K_{n+1} - K_n > 0$ is equivalent to:

$$\frac{Cn_{+1}}{1 - [1/(1+r)]} > K_n\text{, which is inequality (6) in Chapter 2.}$$

Writing [1/(1+r)] as W, equation (4) in Chapter 2 becomes:

$$K_n = \frac{A + \sum_{i=1}^{n} C_i * W^{i-1}}{1 - W^n}.$$

Substituting n+1 for n:

$$K_{n+1} = \frac{A + \sum_{i=1}^{n} C_i*W^{i-1}}{1 - W^{n+1}}$$

$$= \frac{A + \sum_{i=1}^{n+1} C_i*W^{i-1} + C_{n+1}*W^n}{1 - W^{n+1}}$$

$$= \frac{(1 - W^n)K_n + C_{n+1}*W^n}{1 - W^{n+1}}$$

$$= \frac{1 - W^n}{1 - W^{n+1}} + \frac{C_{n+1}*W^n}{1 - W^{n+1}} .$$

Hence:

$$K_{n+1} - K_n = K_n \left(\frac{1 - W^n}{1 - W^{n+1}} - 1\right) + \frac{C_{n+1}*W^n}{1 - W^{n+1}}$$

$$= \frac{K_n (W^{n+1} - W^n) + C_{n+1}*W^n}{1 - W^{n+1}}. \quad \text{(A1)}$$

Since $W < 1$, which implies that $(1 - W^{n+1}) > 0$;

if $K_{n+1} - K_n > 0$, then:

$$[K_n (W^{n+1} - W^n) + C_{n+1}*W^n] > 0.$$

Dividing this inequality through by W^n:

$$K_n (W - 1) + C_{n+1} > 0.$$

Hence: $C_{n+1} > (1 - W) K_n$,

or: $$\frac{C_{n+1}}{1 - W} > K_n.$$

Equivalently: $$\frac{C_{n+1}}{1 - 1/(1+r)} > K_n,$$ which is inequality (5) in Chapter 2.

Multiplying equation (A1) by -1, one obtains:

$$K_{n+1} - K_n = \frac{K_n (W^n - W^{n+1}) - C_{n+1}*W^n}{1 - W^{n+1}}.$$

Replacing n by n+1:

$$K_{n-1} - K_n = \frac{K_{n-1} (W^{n-1} - W^n) - C_n*W^{n-1}}{1 - W^{n+1}}.$$

Then if $K_{n-1} - K_n > 0$,

$$K_{n-1} (W^{n-1} - W^n - C_n*W^{n-1} > 0.$$

Dividing this inequality through by W^n:

$$(1 - W) K_{n-1} - C_n > 0.$$

Hence: $$\frac{C_n}{1 - W} < K_{n-1}.$$

Equivalently: $$\frac{C_n}{1 - 1/(1+r)} < K_{n-1},$$ which is inequality (6) in Chapter 2.

Appendix B

DETERMINATION OF DISCOUNT RATE AND CROP PRICES

This appendix provides further explanation of how the discount rates and crop price parameters in the deterministic and stochastic dynamic programming models were determined. Chapter 3 states that optimal adoption strategies are determined for discount rates of 3%, 6%, and 9%. However, Chapter 3 did not explain why these discount rates were chosen, so an explanation is provided here. Chapter 4 provides a partial explanation of how historical crop prices were adjusted for inflation and technological improvement. Results for the estimation of the technology trend are presented here. Explanation also is provided for how the Markovian price state probabilities were determined for the stochastic model.

The choice of discount rate is important in the determination of the optimal time to replace and possibly change machinery. The optimal time to replace with a new but otherwise identical machine depends on the comparison between a large current expense and many future years of reduced repair costs. The optimal time to replace with alternative machinery also depends on the comparison between possible short-term adjustment costs and increased future net revenues. A relatively high discount rate reduces the value of future net revenues and therefore delays the optimal replacement time until repair costs for the current machinery have increased enough to offset this loss of future value.

The appropriate discount rate for this analysis is a real before-tax cost of capital. The rate must be adjusted for inflation because the future prices and costs used in the dynamic programming model are current values that reflect zero price inflation. In order for the discount rate to be consistent with prices and costs, it also must reflect zero price inflation. The cost of capital is adjusted for inflation by the Consumer Price Index for all items minus shelter (CPI-S) since this index was used to adjust crop prices for inflation. A before-tax cost of capital is appropriate because tax deductions are excluded from this analysis. Use of a before-tax cost of capital therefore provides consistency with before-tax cash flows.

A wide range of values for the appropriate cost of capital can be supported. There are three reasons why such a wide range exists. First, an appropriate discount rate is a weighted average of returns to equity capital and interest rates on borrowed capital (Aplin et al., 1977), and the relative weights vary for different farmers. Second, there are a variety of alternative investments that offer different rates of return to equity capital, largely depending on the risk associated with each investment. Third, average rates of return on equity capital and interest rates on borrowed capital have been higher in some periods than in others, so any average cost of capital depends on the historical period selected. Data for the period 1950-1991 are evaluated here, following Barry's (1980) argument that previous data may be biased by major wars and economic depression.

Barry (1980) shows for the period 1950-1977 that the return to investments in farmland is similar to the returns on stocks and bonds. For that period, the total rate of return (value return plus production return in nominal values) averaged 10.8% per year for farmland, 11.6% for stocks (the Standard and Poors 500 index), 8.5% for a portfolio of stocks and bonds, and 8.9% for a portfolio of stocks, bonds, and farmland. The average annual rate of inflation, as measured by the CPI-S, was 3.3% and the average rate of return on a risk-free asset (3-month Treasury Bills) was 3.9% during this period. For 1950-1991, the total real rate of return for all farm production assets (Federal Reserve Bank, 1985; NAS, various years), including farmland, averaged 3.45% per year. For 1950-1991, the average interest rate, adjusted for inflation by the CPI-S, was 1.28% for Treasury Bills, 2.93% for Moody's Aaa bonds, and 3.85% for Moody's Baa bonds. The average total return to stocks, adjusted for inflation by the CPI-S was 8.56% from 1950 to 1991. From these data, it appears that the average annual rates of return on most diversified investment portfolios range from about 3% to 6%, depending on risk aversion and the proportion of equity capital invested in agriculture.

Interest rates for non-real estate agricultural loans by commercial banks have averaged 1.51% above Aaa bond rates and 0.27% above Baa bond rates for the period 1969-1991 (Federal Reserve Bank, 1986; ERS, various years). The average annual rate for 1977-1991[1], adjusted for inflation by the CPI-S, is 6.63%. However, the 6.63% average real interest rate is heavily influenced by high real interest rates during the 1980's. The average annual rate for 1969-1991, adjusted for inflation by the CPI-S is 5.06%. Yet, either of these average real interest rates on borrowed capital impliy that farmers with a relatively high debt/asset ratio will have a weighted average cost of

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[1] This average reflects all Federal Reserve Districts, whereas the 1969-1976 data are for the Minneapolis Federal Reserve District alone.

capital in the upper end of the 3-6% range of rates of return for equity capital investments.

The replacement analysis is therefore conducted using both a 3% and a 6% discount rate. Additional sensitivity analysis is conducted using a 9% discount rate to reflect the situations of: (1) a risk-taking farmer for which returns to stock market investments are the most appropriate standard for a discount rate; (2) a farmer who borrowed a lot of money in the 1980's when real interest rates ranged from 7-10%; or (3) a highly leveraged farmer who needs high current net revenues to avoid foreclosure. This range of interest rates provides reasonable upper and lower bounds for the effect of the chosen discount rate on the optimal replacement results. Using these three discount rates also facilitates comparison with previous studies, since Smith (1986) used a 6% discount rate and Weersink and Tauber used 3%, 6%, and 9% discount rates for their analyses of optimal machinery selection and replacement.

Adjustment of Crop Prices for Technology Improvement

The 1955-1990 annual average prices for corn and soybeans exhibit a strong negative time trend that is strongly correlated with a positive time trend for average corn and soybean crop yields in Michigan. The functions for the estimation of the crop yield time trend are presented in Chapter 4. The ordinary least squares estimates presented in Table B.1 indicate that the positive time trend for corn and soybean yields is very strong.

Table B.1 Regression Results for Technology Trend in Crop Yields*

Dependent Variable	Constant	Year	R^2
ln(Corn Yield)	-36.53 (-10.29)	0.0207 (11.50)	.796
ln(Soybean Yield)	-24.72 (-6.93)	0.0142 (7.84)	.644

* T-statistics are in parentheses.

The corn and soybean yield trends presented in Table B.2 were calculated by exponentiating the results of Table B.1 and fitting them into the equations:

$YIELD_c = \exp\{a+b*YEAR\}$, and

$YIELD_s = \exp\{c+d*YEAR\}$.

Then the technology adjustment constants (the third and fourth columns of Table B.2) were calculated by dividing the estimated corn and soybean yields for each year by the estimated 1990 corn and soybean yields.

Determination of Price State Probabilities

Price state probabilities also are based on the historical price data. However, 36 years is a very small data set for determining the probability that one price state will follow another, especially since 2 of the 7 price states occur only twice and 2 other price states occur only 4 times in the 36 years (Table B.3). If the observed Markovian price state probabilities (Table B.4) were used directly, some very likely price transitions would not be considered. For example, the

Table B.2 Crop Yield Technology Trends

Year	Corn Yield	Soybean Yield	Corn Adj.	Soybean Adj.
1955	52.15	20.05	0.4844	0.6089
1956	53.24	20.33	0.4946	0.6176
1957	54.35	20.62	0.5049	0.6264
1958	55.49	20.92	0.5155	0.6353
1959	56.65	21.22	0.5262	0.6444
1960	57.84	21.52	0.5373	0.6536
1961	59.05	21.83	0.5485	0.6629
1962	60.28	22.14	0.5600	0.6724
1963	61.54	22.45	0.5717	0.6820
1964	62.83	22.78	0.5837	0.6917
1965	64.15	23.10	0.5959	0.7016
1966	65.49	23.43	0.6083	0.7116
1967	66.86	23.76	0.6211	0.7218
1968	68.26	24.10	0.6341	0.7321
1969	69.69	24.45	0.6473	0.7425
1970	71.15	24.80	0.6609	0.7531
1971	72.63	25.15	0.6747	0.7639
1972	74.15	25.51	0.6888	0.7748
1973	75.71	25.87	0.7032	0.7858
1974	77.29	26.24	0.7180	0.7971
1975	78.91	26.62	0.7330	0.8084
1976	80.56	27.00	0.7483	0.8200
1977	82.24	27.38	0.7640	0.8317
1978	83.97	27.77	0.7800	0.8436
1979	85.72	28.17	0.7963	0.8556
1980	87.52	28.57	0.8129	0.8678
1981	89.35	28.98	0.8300	0.8802
1982	91.22	29.40	0.8473	0.8928
1983	93.13	29.81	0.8651	0.9055
1984	95.07	30.24	0.8832	0.9185
1985	97.06	30.67	0.9016	0.9316
1986	99.09	31.11	0.9205	0.9449
1987	101.17	31.55	0.9398	0.9584
1988	103.28	32.00	0.9594	0.9720
1989	105.45	32.46	0.9795	0.9859
1990	107.65	32.93	1.0000	1.0000

Table B.3 Price State Definitions and Frequencies

Price State	Corn Mean	Corn Range	Soybean Mean	Soybean Range	Obser-vations	Fre-quency
1	2.18	1.56-2.35	5.63	5.16-6.05	8	22.2%
2	2.18	1.56-2.35	6.65	6.11-7.23	4	11.1%
3	2.62	2.36-2.78	5.63	5.16-6.05	4	11.1%
4	2.62	2.36-2.78	6.65	6.11-7.23	6	16.7%
5	2.62	2.36-2.78	10.08	7.49-12.80	2	5.6%
6	3.59	2.79-5.21	6.65	6.11-7.23	2	5.6%
7	3.59	2.79-5.21	10.08	7.49-12.80	10	27.8%

Table B.4 Observed Markovian Price State Probabilities

If Previous Price State was:	Probability of Each Current Price State Is: 1	2	3	4	5	6	7
1	0.75	0.13	0.0	0.13	0.0	0.0	0.0
2	0.0	0.25	0.25	0.0	0.25	0.0	0.0
3	0.25	0.0	0.50	0.25	0.0	0.0	0.0
4	0.0	0.33	0.0	0.67	0.0	0.0	0.0
5	0.50	0.0	0.0	0.0	0.0	0.50	0.0
6	0.50	0.0	0.0	0.0	0.0	0.0	0.50
7	0.0	0.0	0.0	0.0	0.10	0.10	0.80

Table B.5 Assumed Markovian Price State Probabilities, Corresponding to the Historical Mean Prices.

If Previous Price State was:	Probability of Each Current Price State Is: 1	2	3	4	5	6	7
1	0.70	0.10	0.08	0.12	0.0	0.0	0.0
2	0.10	0.23	0.22	0.15	0.15	0.0	0.15
3	0.22	0.18	0.40	0.20	0.0	0.0	0.0
4	0.08	0.20	0.10	0.40	0.07	0.07	0.08
5	0.18	0.10	0.0	0.15	0.20	0.20	0.17
6	0.15	0.0	0.15	0.0	0.15	0.15	0.25
7	0.0	0.0	0.0	0.05	0.05	0.20	0.70

Table B.6 Assumed Markovian Price State Probabilities, Corresponding to the Historical Median Prices.

If Previous Price State was:	Probability of Each Current Price State Is: 1	2	3	4	5	6	7
1	0.70	0.10	0.10	0.10	0.0	0.0	0.0
2	0.10	0.25	0.20	0.25	0.10	0.0	0.10
3	0.20	0.20	0.30	0.20	0.0	0.10	0.0
4	0.08	0.15	0.15	0.35	0.07	0.10	0.10
5	0.18	0.10	0.0	0.22	0.10	0.20	0.20
6	0.15	0.0	0.15	0.25	0.0	0.30	0.15
7	0.0	0.0	0.0	0.30	0.10	0.20	0.40

observed probability of medium corn and medium soybean prices (price state 4) following medium corn and high soybean prices (price state 5) or following high corn and medium soybean prices (price state 6) is zero. Therefore, adjustments were made to the observed probabilities in order to allow for these possibilities. The adjusted probabilities are shown in Tables B.5 and B.6.

The adjusted probabilities were tested for consistency with the historical data using Monte-Carlo simulation. The Monte-Carlo simulation made repeated random draws[2] from a uniform distribution, determined which price state occurred for each draw using the Markovian price state probability matrices (Tables B.5 and B.6), and finally calculated the frequency that each price state occurred. These frequencies were then compared to the historical frequency of each price state (Table B.3).

[2] Five thousand random draws were made with ten different seeds for the random number generator, for a total of 50,000 random draws.

Two sets of price state probabilities are used in the stochastic dynamic programming analyses. Most of the stochastic dynamic programming analyses are based on the price probabilites that replicate the historical frequency that each price state occurs (the probabilities in Table B.5 replicate the frequencies presented in Table B.3) in repeated Monte-Carlo simulations. When these frequencies are divided by the number of total observations and multiplied by the mean corn and soybean prices for each price state, the resulting weighted average prices approximately equal the historical mean prices of $2.80 for corn and $7.46 for soybeans.

The other set of price state probabilities (Table B.6) reflect an expectation that the combination of high corn and high soybean prices (price state 7) will not occur as frequently in the future as it did in the period 1955-1990. Eight out of the ten historical observations of prices corresponding to price state 7 occurred during the 1970's, a period of dramatic structural change in the world grain markets. In order to evaluate optimal adoption strategies for farmers that do not expect crop prices to frequently return to the levels of the 1970's, the probabilities for price state 7 were greatly reduced in the second set of price state probabilities. The second set of price state probabilities also were adjusted to approximately replicate the historical median prices when weighted average corn and soybean prices were calculated from the price state frequencies of repeated Monte-Carlo simulations.

Appendix C

MODIFICATIONS OF THE CERES-MAIZE AND SOYGRO MODELS

The current versions of the CERES-MAIZE and SOYGRO crop growth simulation models distributed by the IBSNAT project[1] do not include any mechanism for showing the effects of surface residues. This Appendix describes modifications made to CERES-MAIZE version 2.1S and SOYGRO version 5.42 in order to include surface residue effects on corn and soybean growth. The source code modifications are listed in Appendix H. Many of the modifications to CERES-MAIZE were developed by Frederic Dadoun of the Dept. of Crop and Soils Science at Michigan State University. Dadoun's modifications, which are acknowleged below, were extended and refined for this analysis. Similar modifications were then made to the SOYGRO model so that it would show the same kinds of surface mulch effects as the modified CERES-MAIZE model.

The modifications to the CERES-MAIZE and SOYGRO models start with the addition of a subroutine developed by Dadoun to estimate daily amounts of surface residues and the proportion of soil surface covered with residues. Surface residues decompose throughout the crop season, and provide additional nitrogen to corn after decomposed residues are washed into the soil by rainfall and mineralized. The modifications to the CERES-MAIZE and SOYGRO models also account for the effects of surface mulch on soil evaporation and soil temperature. Surface mulch reduces soil evaporation by insulating the soil surface from solar radiation and reducing air flow over the soil surface. Surface mulch

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[1] International Benchmark Sites Network for Agrotechnology Transfer, funded by the US Agency for International Development, and implemented by the University of Hawaii and other collaborators.

also reduces soil temperature (see the references in Chapter 4) by reflecting more solar radiation than the soil surface and by insulating the soil surface (Van Doren and Allmaras, 1978).

Both the CERES-MAIZE and SOYGRO models emphasize water balance dynamics and the effects of soil moisture stresses on plant growth. Both models estimate daily soil moisture contents in each soil layer, daily water uptake by the growing plant, and daily moisture stress factors. Since soil evaporation is one of the principal ways that the soil loses moisture, reduced soil evaporation reduces plant moisture stresses and contributes to increased crop yields in both models.

Soil temperature is completely ignored by the SOYGRO model and is considered by the CERES-MAIZE model only for the purpose of regulating soil nitrogen dynamics (Jones and Kiniry, 1986; Godwin and Jones, 1991). Yet the CERES-MAIZE model does estimate daily temperatures in each soil layer, so the soil temperature effects on corn growth described in Chapter 4 were considered simply by adding other mechanisms for soil temperature effects to the model. For the SOYGRO model, both a subroutine for calculating daily soil temperature and mechanisms for soil temperature effects on soybean growth had to be added.

Three important mechanisms for soil temperature effects on corn and soybean growth were added to the CERES-MAIZE and SOYGRO models. First, the rate of phenological development before emergence and during juvenile, or vegetative growth stages was changed from being a function of air temperature to being a function of both air and soil temperature. Second, photosynthate production during the same growth stages was made a function of soil temperature. In CERES-MAIZE, this is accomplished by making the rate of leaf appearance be a function of soil temperature, and each leaf adds to the amount of intercepted solar radiation and photosynthate production. In SOYGRO, a temperature stress factor that reduces the rate of photosynthesis is changed from being a function of air temperature to being a function of soil temperature during these early growth stages. Third, a soil temperature stress factor was added to root growth in both models, following the root growth model of Jones et al. (1991).

Effects of no-till systems on soil physical characteristics, such as increased soil bulk density, increased soil acidity, and changes in the distribution of organic matter (Blevins et al., 1983; Blevins et al., 1985) were not incorporated in the CERES-MAIZE and SOYGRO models. Such effects have been documented in the agronomy literature, but they often require several years to be detectable and have not been as consistent as soil temperature and soil evaporation effects. Also, the effects of these changes in soil physical characteristics on plant growth generally have not been separated from soil temperature effects on plant growth. Since suitable data were not available to calibrate the effects of soil physical characteristics on corn and soybean growth in no-till production, any change in soil parameters for the no-till system would have been very arbitrary. Therefore, possible changes in soil bulk density, soil acidity, and the distribution of soil organic matter associated with no-till systems were ignored.

Specific Modifications to CERES-MAIZE

Basic Structure of CERES-MAIZE version 2.1S

The FORTRAN code for CERES-MAIZE 2.1S consists of a main program, "MAIN.FOR", and 68 subroutines. Although the number of subroutines is large, they fall into 7 functional groups. These groups and specific subroutines that were modified, are listed in Table C.1

Table C.1 Subroutine Groups in CERES-MAIZE

Subroutine Group	Modified Subroutines Within each Group
1. Initialization	IPNIT (initializes nitrogen parameters)
2. Water Balance	POTEV (estimates potential evaporation)
3. Nitrogen Balance	NTRANS (tracks soil nitrogen dynamics) SOLT (estimates soil temperatures)
4. Phenology	PHENOL (determines growth stages)
5. Growth	GROSUB (estimates photosynthate production and leaf emergence) ROOTGR (estimates root growth in mass and distribution in the soil)
6. Output	
7. Utilities	

The initialization subroutines read input files and set initial parameters. The water balance subroutines estimate soil moisture dynamics. The nitrogen balance subroutines estimate soil nitrogen dynamics. The phenology subroutines determine when the plant progresses from one growth stage to the next and reset parameters for different growth stages as needed. The growth subroutines determine the amount of photosynthate (biomass) produced, its partitioning among leaves, stem, roots, and reproductive organs, and the growth in size, mass, and number of those plant parts. Output and utility subroutines write output files and perform various repetitive tasks.

Dadoun's Modifications

The subroutine IPNIT reads an input file containing levels and depths of incorporation of crop residue, which the nitrogen balance subroutines use to estimate the contribution of crop residues to the soil nitrogen pool through mineralization (Godwin and Jones, 1991). This input file is read as "FILE4" by CERES-MAIZE, and must have the filename extension, ".MZ4". Dadoun made IPNIT partition these crop residues between surface residues and incorporated residues depending on the depth of incorporation (variable SDEP). He assumed that if the depth of incorporation is no greater than 1 cm., all crop residues should be treated as surface mulch. This implies that a no-till system is used. An incorporation depth of 1-10 cm. would leave 70% of crop residues on the surface and an incorporation depth of 10-20 cm. would leave 30% of crop residues on the surface. An incorporation depth of 20 cm. or more corresponds to moldboard plowing in which all crop residues are assumed to be incorporated.

Dadoun then added a subroutine, MULCHE, to calculate decomposition of surface mulch over time and its contribution of organic matter for nitrogen mineralization. He assumed that surface mulch decomposes by exp(-.0075) per day, subject to the influence of air temperature and soil moisture. A few lines added to the NTRANS subroutine (lines 176-

182) cause water infiltration to bring this organic matter from the surface into the soil. Dadoun also added mulch effects to reduce soil evaporation and increase albedo (reflectance of solar radiation) in subroutine POTEV. He also added a mulch cover effect to the calculation of soil temperature in subroutine SOLT. Finally, Dadoun had the PHENOL subroutine use soil thermal time in place of the daily thermal time based on air temperature (DTT) to calculate plant development until the appearance of the 9th leaf in the third growth stage. Soil thermal time was defined as the accumulation of temperature in the top soil layer minus the same base temperature as CERES-MAIZE uses for the DTT based on air temperature. A common block, "RESI", was added to pass values of mulch variables between these subroutines.

Additional Major Changes Made to CERES-MAIZE

Three substantial changes and additions were made to Dadoun's modifications of CERES-MAIZE for surface mulch effects. First, the accumulation of thermal time to regulate phenological stages was made a weighted average of soil and air temperature, rather than soil temperature alone, and the period of soil temperature influence was restricted to growth stages 9, 1, and 2 that end with tassel initiation. This weighted average of soil and air temperature also was used to regulate the rate of leaf appearance during growth stage 2. Second, portions of surface mulch were incorporated in the soil during planting and anhydrous ammonia application. Third, a soil temperature stress factor was added to the estimation of root density in each soil layer (by changing the calculation of variable RLDF in subroutine ROOTGR).

A weighted average of soil and air temperature was used to calculate thermal time because it was observed that basing thermal time on soil temperature alone greatly altered phenological development for corn grown with conventional tillage. Since phenological development in CERES-MAIZE has passed many validation tests based on empirical data (Kiniry, 1991), phenological development for the standard and modified models must be consistent for conventional tillage. Weighted averages of soil and air temperature kept errors between estimated growth stage dates and observed growth stage dates at nearly the same level as exhibited by CERES-MAIZE 2.1S. During growth stage 9 (germination to seedling emergence), soil temperature in the top layer is given a 50% weight and air temperature is given a 50% weight. During growth stages 1 and 2, the respective weights are 30% and 70%, respectively.

The partial incorporation of surface mulch into the soil during planting and anhydrous ammonia application is well documented in the agronomy literature (Griffith et al., 1986). Approximately 10% of surface residue is incorporated during planting (Dickey et al., undated). It was assumed that the same amount would be incorporated when anhydrous ammonia is knifed into a no-till field because a similar coulter would be used. Incorporating these portions of the surface residue also provided much closer agreement between the values reported for mulch cover at planting time (Griffith et al., 1986) and later in the season (Parker, 1962) and the values estimated by the modified CERES-MAIZE model.

The soil temperature stress factor, RTLTF, was added to the estimation of corn root growth because effects of soil temperature on root growth are well documented (see Chapter 4) and because a formula to calculate this effect had already been proposed by Jones et al. (1991). The formula proposed by Jones et al. (1991) is:

$$RTLTF = \sin[1.57 * (ST(L) - TBASE) / (TOP - TBASE)],$$

where ST(L) is the soil temperature in a specified layer, TBASE is the lowest temperature at which growth occurs, and TOP is the optimal temperature for growth. This formula also is used in the EPIC model (Williams, Jones, and Dyke, 1990, p. 57).

<u>Parameter Changes Made in CERES-MAIZE</u>

Additional changes were made to parameters in Dadoun's version of CERES-MAIZE in order to get results from the model to closely approximate results reported in the agronomic literature. These changes were in the calculation of surface mulch (variable MULCH, measured in tons per ha.) in Dadoun's subroutine, MULCHE, the calculation of mulch cover (variable MULCHCOV, measured in percent) in subroutine SOLT, and the calculation of the current day's input into a 5-day moving average temperature in the top soil layer (variable TMA(1)) in subroutine SOLT. One additional change was made to the radiation use efficiency coefficient in CERES-MAIZE 2.1S, based on results reported by Kiniry et al. (1989). This coefficient, used in the calculation of the variable PCARB in subroutine GROSUB, was changed from 5.0 to 3.9. The change in the radiation use efficiency coefficient has the effect of reducing estimated corn yields for ideal growing conditions to realistic levels.

Dadoun calculated the daily value of the variable, MULCH, as:

MULCH=MULCH*exp(-.0075*amin1(TEDECF,WADECF).

The MULCH value on the right-hand side of the equation is the previous day's MULCH value. Based on results reported by Parker (1962), this calculation was changed to:

MULCH=MULCH*exp(-.009*aminl(TEDECF,WADECF).

Based on research by Gregory, (1982) Dadoun calculated the daily value of the variable, MULCHCOV, as:

MULCHCOV=1.0-exp(-.4*MULCH/1000).

However, in order to get better agreement with CERES-MAIZE mulch cover estimates and estimates reported by Griffith et al. (1986) and Sloneker and Moldenhauer (1977), this calculation was changed[2] to:

MULCHCOV=1.0-exp(-.35*MULCH/1000).

Finally, CERES-MAIZE uses a 5-day moving average soil surface temperature, variable TMA(1), in its calculation of temperatures for each soil layer. Dadoun calculated the current day's input into this 5-day moving average as:

```
TMA(1)=(1.0-ALBEDO-0.227*MULCHCOV)*(TEMPM+(TEMPMX-TEMPM)*
     SQRT(SOLRAD*0.005))+(ALBEDO+0.227*MULCHCOV)*TMA(1).
```

Again, the value of TMA(1) on the right-hand side of the equation is the previous day's value. Based on the soil temperature results reported by Bronson (1989), this calculation was changed to:

```
TMA(1)=(1.0-ALBEDO-0.42*MULCHCOV)*(TEMPM+(TEMPMX-TEMPM)*
     SQRT(SOLRAD*0.02))+(ALBEDO+0.38*MULCHCOV)*TMA(1).
```

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[2] Dadoun's model used a slightly different formula in the subroutine POTEV, which was not found in time to be corrected. In subroutine POTEV, the coefficient for the negative exponential function is 0.32 rather than 0.35. This error results in a slightly lower value of surface mulch cover being used for the calculation of soil evaporation than for the calculation of soil temperature. However, Gregory's (1982) results ranged from a coefficient of 0.32 to 0.40, so any of these estimates can be defended.

Model Validation

Suitable data for the validation of the model for both tillage systems have not yet been found, so the modified CERES-MAIZE model must be viewed as preliminary. However, the modified CERES-MAIZE model produced results that very closely agreed with results for an irrigated trial using conventional tillage near Mendon, in St. Joseph County, Michigan (Table C.2).

Table C.2 Validation Results for 1988 at Mendon, Michigan

	PREDICTED	OBSERVED
SILKING DATE	200.0	200.0
GRAIN YIELD (KG/HA)	10428.0	10848.0
KERNEL WEIGHT (G)	0.30	0.29
GRAINS PER SQ METRE	2919.0	3279.0
GRAINS PER EAR	430.6	484.0
MAX. LAI	4.2	5.1
BIOMASS (KG/HA)	18524.0	18762.0
STRAW (KG/HA)	9712.0	9370.0
GRAIN N%	1.6	1.4
TOT N UPTAKE (KG N/HA)	183.5	208.7
STRAW N UPTAKE	46.4	78.2
GRAIN N UPTAKE	137.0	130.5

Results at the Cupp-Farm, Mendon Michigan on an Oshtemo sandy loam soil. Hybrid Pioneer 3475 was planted on May 5 with 10 kg N/ha as diammonium phosphate, after 200 kg N/ha was applied as anhydrous ammonia on April 20. The field received a total of 347 mm. of irrigation and 155 mm. of rainfall from March 15 until September 15.

Specific Modifications to SOYGRO

Basic Structure of SOYGRO version 5.42

The FORTRAN code for SOYGRO 5.42 consists of a main program, "GRO.FOR", and 35 subroutines. The SOYGRO subroutines can be divided into 6 functional groups. These groups and specific subroutines that were modified, are listed in Table C.3

Table C.3 Subroutine Groups in SOYGRO

Subroutine Group	Modified Subroutines Within each Group
1. Initialization	IPCROP (reads a crop parameters file) IPSOIL (initializes soil parameters)
2. Water Balance	WATBAL (calculates daily water balance)
3. Phenology	GPHEN (determines growth stages)
4. Growth	CROP (calls growth subroutines) PHOTO (estimates photosynthate production) VEGGR (partitions photosynthate among plant organs)
5. Output	
6. Utilities	

Modifications Made to SOYGRO Source Code

SOYGRO was modified to exhibit similar surface mulch effects on plant growth as the modified version of CERES-MAIZE. As much as possible, the same source code was used in both models. However, SOYGRO was developed independently of CERES-MAIZE and emphasizes different aspects of plant growth (Wilkerson, 1983; Jones et al., 1991). Therefore, different mechanisms sometimes had to be used for surface mulch effects in SOYGRO than were used for CERES-MAIZE. Modifications to the SOYGRO source code included introducing soil temperature calculations, adding a mulch subroutine (MULCHS), introducing surface mulch effects on soil evaporation and soil temperature, making early phenological development and photosynthesis rates partly dependent on soil temperature, and adding a soil temperature stress factor to the estimation of root growth.

Additions to three subroutines were made in order to introduce soil temperature estimates. Source code for soil temperature initialization was taken from the CERES-MAIZE subroutine, SOILNI, and divided between SOYGRO subroutines, IPSOIL and CROP. The daily soil temperature calculations from the CERES-MAIZE subroutine, SOLT, were placed in the new SOYGRO subroutine, MULCHS. Subroutine MULCHS was called within SOYGRO subroutine WATBAL.

In addition, to calculating daily temperatures for each soil layer, subroutine MULCHS estimated daily surface residue decomposition and percent coverage of the soil surface with crop residue (variable MULCHCOV). These estimates were made with the same formulas and parameters used in the CERES-MAIZE subroutine, MULCHE. Initial surface residue weights were added to SOYGRO's input file of crop parameters, "CROPPARM.SBO", which is read by subroutine IPCROP. As in CERES-MAIZE, a common block of variables named "RESI.BLK" was defined in order to pass crop residue variables between subroutines.

Additions were made to the WATBAL subroutine, so that after it calls subroutine MULCHS, it uses the mulch cover estimates to adjust soil evaporation. This adjustment was made using the same formulas and parameters used in the CERES-MAIZE subroutine, POTEV. Since the WATBAL subroutine also calculates a root length density factor (RLDF) when estimating root mass and distribution, the same soil temperature stress factor used in the calculation of RLDF in CERES-MAIZE was introduced to the calculation of RLDF in SOYGRO's WATBAL subroutine.

The VEGGR subroutine in SOYGRO that partitions photosynthate (biomass) among various plant parts according to the current growth stage also calculates a root length density factor (RLDF). Therefore, the soil temperature stress calculation was also added to the VEGGR subroutine.

A soil temperature effect was added to soybean phenological development during growth stages V0 and V1 (variables NVEG0 and NVEG1 in SOYGRO). As with CERES-MAIZE, it was observed that phenological development under conventional tilage was distorted when based entirely on soil temperature during these stages, so a weighted average of soil and air temperatures was used. For both of these stages, the accumulation of thermal time was based 30% on the temperature of the top soil layer and 70% on air temperature. These weights were chosen because they caused minimal distortion of phenological development under conventional tillage, while still allowing for a soil temperature effect under no-till. The change in the calculation of thermal time accumulation for growth stages V0 and V1 was made in SOYGRO subroutine, GPHEN.

The SOYGRO subroutine, PHOTO, regulates photosynthesis rates with both a moisture stress factor and a temperature stress factor. The temperature stress factor (variable TPHFAC) for growth stages V0 and V1 was calculated using a weighted average of the temperature in the top soil layer (30%) and air temperature (70%). Calculation of TPHFAC was also changed from a very crude interpolation procedure using the TABEX subroutine to direct estimation using a cubic function. Parameters for the cubic function are based on data presented by Hofstra and Hesketh (1975). Wilkerson et al. (1983) chose a logistic function to represent the Hofstra and Hesketh (1975) results in SOYGRO, but a cubic function provides a much better fit. Parameters for the cubic function were added to the "CROPPARM.SBO" file and read by subroutine IPCROP. The formula used to calculate TPHFAC is:

$$TPHFAC = (0.54*TDAY + 0.66*TDAY^2 - 0.123*TDAY^3) / 160,$$

where TDAY is a daily thermal time increment analogous to a growing degree day. During growth stages V0 and V1, TDAY is calculated as the weighted average of temperature in the top soil layer and air temperature.

One additional parameter change was made to the estimation of photosynthesis rates in order to raise the highest estimates of soybean yields to levels observed in Michigan soybean variety trials (Vitosh et al. 1991). SOYGRO was calibrated in Florida, where soybean varieties are adapted to abundant solar radiation. The functional relationship between photosynthesis rates and solar radiation levels not only varies greatly within species, but also is quadratic rather than linear in form, with a much higher response at low solar radiation levels than at high levels (Zelitch, 1971). SOYGRO includes a parameter (PHAC3) in the soil data file input file (read as FILE2) for making a linear adjustment to the response of photosynthesis to solar radiation levels for a particular location. Due to its greater latitude, Michigan receives much less solar radiation than Florida. Therefore, the PHFAC parameter was set at 1.10 for this analysis, which had the effect of increasing photosynthesis rates by 10% when not constrained by moisture or temperature stresses.

Appendix D

TRACTOR REMAINING VALUE CALCULATIONS

Remaining values, also called salvage or trade-in values, of farm machinery are critical parameters in an optimal replacement analysis, but they are difficult to estimate. Remaining values have been shown to be affected by age, usage, condition, size, and manufacturer (Perry et al., 1990). Even after all of these factors have been considered, remaining values are still highly variable, due to such factors as location and asymmetric information between the buyer and seller regarding the true condition of the machinery (Akerloff, 1970). Remaining values also are sensitive to macroeconomic variables such as interest rates and aggregate farm income (Perry et al., 1990).

Perry et al. (1990) performed a great service by analyzing a large data set of auction prices for tractors and quantifying the effects of most of these variables on tractor remaining values. By using the Box-Cox flexible functional form for their estimation, Perry et al. also did not impose a functional form on the depreciation patterns for tractors. However, the Perry et al. estimates for tractor remaining values sometimes are not suitable for farm-level analyses.

Although Perry et al. were able to detect separate, statistically significant effects for age and usage per year in a heterogeneous sample, accumulated usage is the dominant concern for an individual farmer. Very little in a tractor physically deteriorates with time if the tractor is not used. After accumulated usage is considered, any separate effect of age on remaining value usually reflects a belief that the newer tractor is technologically superior. Indeed, Perry et al.

(1990) admit in a footnote that their age variable captures some of the effect of usage on remaining values. Thus, their estimate of the effect of usage on remaining value is biased if age is not varied. This bias becomes important when the choice of tillage technology implies two different levels of tractor usage per year.

A second difficulty in applying Perry et al.'s estimates to a farm-level replacement problem is that the Box-Cox estimates are for nonlinear transformations of the original variables. A little algebra can produce a dollar estimate of remaining value for specified levels of each variable, but a computer is needed to do it quickly.

An exponential function of accumulated usage and the square of accumulated usage was found which closely approximates Perry et al.'s results for tractor remaining values and avoids the two problems discussed above. First, Perry et al.'s estimates for remaining value were calculated for the cases of a 140 HP tractor used 800 hours per year, a 140 HP tractor used 400 hours per year, and an 80 HP tractor used 400 hours per year. Also, a 4% after-tax real interest rate was assumed. Parameters for manufacturer, real net farm income, location, and auction type were kept the same as in Perry et al.'s examples (see Perry et al's footnote 10). The remaining value estimates were extended for 30 years at these rates of annual usage, and transformed to dollar values. Third, the natural logarithms of these estimates were regressed on the natural logarithms of the usage variables. The usage variables are accumulated hours of use, divided by 1000[3] (AHRS), and the same measure squared (AHRS2). The equation estimated for each case was:

$$\ln RV = \ln \beta_0 + AHRS * \ln \beta_1 + AHRS2 * \ln \beta_2 + \epsilon.$$

Results for these estimates are shown in Table D.1.

Table D.1 Results for the RV Regression on Total Usage Variables

Case	β_0	β_1	β_2	obs.	R^2
140 HP tractor, 800 hrs/yr.	-.5573	-.0751	-.0036	20	.9997
140 HP tractor, 400 hrs/yr.	-.4519	-.1484	-.0126	20	.9998
80 HP tractor, 400 hrs/yr.	-.4849	-.1194	-.0080	25	.9998

After exponentiating, the equations for estimating RV as a function of accumulated usage are:

Case	Estimating Equation
140 HP tractor, 800 hrs/yr.	$RV = .5727 * .9277^{AHRS} * .9964^{AHRS2}$
140 HP tractor, 400 hrs/yr.	$RV = .6364 * .8621^{AHRS} * .9874^{AHRS2}$
80 HP tractor, 400 hrs/yr.	$RV = .6158 * .8875^{AHRS} * .9921^{AHRS2}$

Analysis of the residuals (Table D.2) indicated that these estimates are very close to Perry et al.'s estimates after the first year and continuing until after about 20 or 25 years. For very old tractors these estimates tend to be increasingly higher than Perry et al.'s estimates. Since tractors are rarely kept longer than 20 or 25 years at these rates of annual usage, the numbers of observations were imited to those indicated in order to get a closer approximation.

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[3] This measure is used by the American Society of Agricultural Engineers (1987) to estimate accumulated repair costs.

Table D.2 Residuals from the Approximation of RV Estimates based on Age and Hours per Year using a Function of Cumulative Hours*.

	140 HP, John Deere tractor (800 HRS/YR)			80 HP, John Deere tractor (400 HRS/YR)		
Year	Estimate from age and hrs.	Estimate from only cum. hrs.	Residual	Estimate from age and hrs.	Estimate from only cum. hrs.	Residual
1	0.5482	0.5381	0.0101	0.5960	0.5863	0.0097
2	0.5070	0.5032	0.0038	0.5616	0.5568	0.0048
3	0.4681	0.4685	-0.0003	0.5288	0.5275	0.0013
4	0.4313	0.4341	-0.0028	0.4973	0.4984	-0.0012
5	0.3964	0.4004	-0.0040	0.4671	0.4698	-0.0027
6	0.3633	0.3676	-0.0043	0.4381	0.4417	-0.0036
7	0.3321	0.3360	-0.0039	0.4103	0.4141	-0.0038
8	0.3025	0.3056	-0.0031	0.3836	0.3874	-0.0037
9	0.2747	0.2767	-0.0021	0.3581	0.3614	-0.0033
10	0.2484	0.2494	-0.0010	0.3336	0.3363	-0.0026
11	0.2238	0.2238	0.0000	0.3102	0.3121	-0.0019
12	0.2007	0.1998	0.0009	0.2879	0.2890	-0.0011
13	0.1791	0.1776	0.0015	0.2665	0.2669	-0.0003
14	0.1590	0.1572	0.0018	0.2462	0.2458	0.0004
15	0.1403	0.1384	0.0018	0.2268	0.2259	0.0009
16	0.1230	0.1214	0.0016	0.2084	0.2070	0.0014
17	0.1070	0.1059	0.0011	0.1909	0.1892	0.0017
18	0.0923	0.0920	0.0003	0.1743	0.1725	0.0018
19	0.0790	0.0796	-0.0006	0.1587	0.1569	0.0017
20	0.0668	0.0685	-0.0017	0.1439	0.1423	0.0015
21	0.0558	0.0587	-0.0028	0.1299	0.1288	0.0011
22	0.0460	0.0500	-0.0040	0.1168	0.1162	0.0006
23	0.0373	0.0425	-0.0051	0.1046	0.1046	-0.0001
24	0.0297	0.0359	-0.0062	0.0931	0.0940	-0.0009
25	0.0230	0.0302	-0.0071	0.0824	0.0842	-0.0017
26	0.0174	0.0253	-0.0079	0.0725	0.0752	-0.0027
27	0.0126	0.0210	-0.0084	0.0633	0.0670	-0.0037
28	0.0088	0.0175	-0.0087	0.0549	0.0596	-0.0047
29	0.0057	0.0144	-0.0087	0.0472	0.0528	-0.0056
30	0.0034	0.0118	-0.0085	0.0401	0.0467	-0.0066

* The remaining value (RV) estimates based on age and hours are based on Perry et al. (1990). The RV estimates based on cumulative hours alone are based on the results of Table D.1.

Appendix E

MACHINERY COST ESTIMATES

This appendix explains how machinery cost parameters were determined. Machinery prices, fuel consumption, repair costs, and operating rates, all vary considerably, so a range of values is plausible for each variable. Therefore, it is important to identify the source of each machinery value used in the analysis.

All repair cost estimates are based on machinery list prices (Table E.1). Prices for the 140 HP tractor and 85 HP tractor were taken from suggested retail prices listed for John Deere 4455 and 2955 tractors (NAEDA, 1992). Prices for these specific models were chosen because they are comparably equipped with a cab and air conditioning. Many machinery price guides, such as Snyder (1991) and Fuller et al. (1992) quote prices for tractors with less than 100 HP that are not equipped with cabs. However, a comparison of similarly equipped tractors is needed to avoid biasing the analysis of adoption strategies.

Average 1991 list prices for the moldboard plow, disc harrow, row cultivator and sprayer were taken from Snyder (1991). Price estimates for the planters, field cultivator, stalk shredder and NH_3 applicator in were taken from Fuller et al. (1992). Fuller et al. reported purchase prices, so these were divided by 0.9 to estimate list prices. The price of the NH_3 applicator also was multiplied by 0.8 because the only price listed by Fuller et al. was for a size that appears to be 25% larger than the size assumed for this analysis[4].

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[4] Fuller and McGuire do not report a size for their anhydrous ammonia applicator. However, the operating rate of 12.73 acres per hour that they report corresponds to approximately 25 feet of width with standard assumptions used for speed and field efficiency. Fuller and

Machinery sizes and operating speeds were checked for compatibility with 140 HP and 85 HP tractors using draft power estimates by White (1977), Hunt (1983), and Bowers (1987). Power requirements are limiting or nearly limiting for the moldboard plow, disc harrow, and NH_3 applicator.

Table E.1 Machinery List Prices

Machinery Item	size	List Price
140 HP tractor		$60,875
85 HP tractor		$41,513
Moldboard Plow	5 18-inch bottoms	$10,064
Disc Harrow	20 feet	$12,968
Field Cultivator	20 feet	$6,412
Conv. Planter	8 30-inch rows	$17,753
No-till Planter	8 30-inch rows	$21,365
Row Cultivator	8 30-inch rows	$5,040
NH_3 Applicator	20 feet, 8 knives	$13,401
Stalk Shredder	12 feet	$7,599
Sprayer	30 feet	$3,917

Calculation of per acre cost estimates for machinery repairs and labor requires that machinery operating rates in acres per hour be determined. The operating rates reported in Table 4.7 are determined by multiplying the machinery width (in feet) by the operating speed (in mph) and field efficiency, then dividing by the constant, 8.25 (Bowers, 1987). The operating speeds are based on Hunt (1983), ASAE Standards

McGuire also report that their anhydrous ammonia applicator requires a tractor of 160 HP, 20 more HP than is assumed to be available in this analysis.

(1987), and Richey (1982)[5]. Some operating speeds were lowered slightly from values suggested by these references in order to keep the draft requirements within the range that a 140 HP tractor can handle. Field efficiencies are based on Bowers (1987), ASAE Standards (ASAE, 1987), and Richey (1982).

Average machinery repair costs per acre (Tables E.2 and E.3)) for all machinery except the tractors and planters were calculated from list prices, repair cost factors proposed by Rotz and Bowers (1991), and the operating rates reported in Table 4.7. These estimates are based on average repairs over the entire working life of the machinery, as also defined by Rotz and Bowers (1991).

Annual repair costs for tractors and planters (Tables 4.8 and 4.9) are based directly on the formulas proposed by Rotz and Bowers (1991) and the annual usage of each machine. The annual usage for the conventional planter is 80 hours and the annual usage for the no-till planter is 82 hours. The annual usage for the 140 HP tractor is 693 hours if the conventional tillage system is used and only the direct fieldwork listed in Table A43.2 is considered. The annual usage for either the 140 HP tractor or the 85 HP tractor is 336 hours if the no-till system is used and only the direct fieldwork listed in Table A43.3 is considered. However, it is customary to add roughly another 10% for trips between the farmstead and the fields. Also, tractors are normally used during harvest operations to haul grain wagons. When the direct

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[5] Clarence B. Richey reviewed and adjusted machinery cost coefficients for an M.S. thesis by Krause (1983) in October 1982. Richey, formerly in the Dept. of Agricultural Engineering at Purdue University, is one of the most respected authorities on questions concerning machinery costs.

tractor usage for each of the alternative tillage systems was multiplied by 1.18, the resulting usage was approximately 800 hours for the conventional tillage system and 400 hours for the no-till system. Therefore, the values of 800 hours and 400 hours were used to calculate annual tractor repair costs and trade-in values.

Fuel requirements are based on estimates for a moderate soil draft rating by Siemens et al. (1985). Diesel fuel requirements, in gallons per acre are multiplied by $0.84 per gallon, the average price reported for the North Central region in April 1990 (Agricultural Statistics Board, 1991). Fuel and oil costs then are calculated by multiplying fuel cost per acre by 1.15 (Bowers, 1987).

Because harvest operations play no role in this analysis, harvesting costs were not estimated, but simply taken from enterprise budgets prepared by Snyder (1990). Equal harvesting costs are assumed for the alternative tillage systems. Since corn drying costs do vary with grain yields, drying costs were estimated by multiplying per acre corn yields by $0.17 per bushel. This value was suggested by Ed Martin (1992), an extension associate at Michigan State University, for the preparation of budgets for irrigation investments.

Table E.2 Machinery Operations Performed, Conventional Tillage

Crop and Operation	Fuel&Oil $/acre	Repairs $/acre	Labor hrs. per acre
Corn			
Chop stalks (after corn)	0.72/2	0.81/2	0.150/2
Moldboard plow	1.79	1.36	0.276
Disc	0.63	0.43	0.113
Spray herbicide	0.19	0.13	0.088
Field cultivate	0.58	0.21	0.092
Plant	0.53	var.	0.154
Apply NH_3	0.68	0.69	0.139
Row cultivate	0.48	0.26	0.134
	------	------	-------
All operations	5.24	3.91	1.071
Soybeans			
Chop stalks	0.72	0.81	0.150
Moldboard plow	1.79	1.36	0.276
Disc	0.63	0.43	0.113
Spray herbicide	0.19	0.13	0.088
Field cultivate	0.58	0.21	0.092
Plant	0.53	var.	0.154
Row cultivate	0.48	0.26	0.134
Row cultivate	0.48	0.26	0.134
	------	------	-------
All operations	5.41	3.89	1.141

Table E.3 Machinery Operations Performed, No-Till Technology

Crop and Operation	Fuel&Oil $/acre	Repairs $/acre	Labor hrs. per acre
Corn			
Spray herbicide	0.19	0.13	0.088
Chop stalks (after corn)	0.72/2	0.81/2	0.150/2
Plant	0.48	var.	0.159
Spray herbicide	0.19	0.13	0.088
Apply NH_3	0.68	0.69	0.139
	------	------	-------
All operations	1.91	1.35	0.569
Soybeans			
Spray herbicide	0.19	0.13	0.088
Chop stalks	0.72	0.81	0.150
Plant	0.48	var.	0.159
Spray herbicide	0.19	0.13	0.088
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All operations	1.59	1.07	0.505

Appendix F

DETAILED OPERATION DATE AND CROP YIELD RESULTS

This Appendix presents more detailed results than are presented in Chapter 5 for operation dates and crop yields. The purpose is to provide a complete picture of the variation in these results to those who want to see more than a summary. The operation dates also are provided in order that anyone wishing to duplicate the average yield results can do so.

Operation Dates

Operation dates are presented as Julian dates for corn planting, soybean planting, and NH_3 application in Tables F.1-F.12. The relative dates for corn planting and NH_3 application correspond to each other, so the first NH_3 application date was for corn planted on the first planting date.

In Tables F.1, F.4, and F.5 the first 3 corn planting dates are for corn following soybeans, the last three planting dates are for corn following corn, and the middle planting date is split equally between the two corn sequences. For the no-till system, corn planting dates were allocated between corn following corn and corn following soybeans according to soil temperature and moisture conditions. For the first two planting dates, if the temperature in the first soil layer was less than 14° C., corn after soybeans was planted. Soybean residue covered the soil much less than corn residue, so this practice allows the soil to warm up more quickly after planting and speed emergence. Other corn planting days were allocated to corn after soybeans (up to 3.5 days total) if the soil under soybean residue was warm enough and dry enough for planting but the soil under corn residue did not satisfy these criteria. Any remaining corn after soybean acreage was planted after the planting of corn after corn was complete. In Table 5.10, dates of planting corn after soybeans are underlined and the corn planting date split between the two corn sequences is indicated by bold print.

Crop Yields

Corn yields by corn sequence for various planting dates are presented in Tables F.13, F.15, F.17, and F.19. Soybean yields by planting date are presented in Tables F.14, F.16, F.18, and F.20. Corn yields are presented for eight planting dates. The average of the two yields marked "SPLIT" was included with corn yields for the other six dates to calculate annual corn yield means. The variation in yields by planting date is particularly noticeable for corn and is a powerful demonstration of the benefits obtained from comparing alternative technologies using multiple planting dates rather than only one planting date.

Table F.1 Corn Planting Dates, MB Plow, 100% Fall Plowed

Year	C/S*	C/S	C/S	SPLIT*	C/C*	C/C	C/C	Mean
1953	125	126	129	130	131	134	135	130.0
1954	118	119	120	121	123	124	125	121.4
1955	118	119	120	121	123	124	125	121.4
1956	121	134	138	139	140	141	143	136.6
1957	119	120	121	122	123	124	125	122.0
1958	121	122	123	124	125	126	127	124.0
1959	121	122	123	124	125	126	127	124.0
1960	118	119	123	124	125	134	135	125.4
1961	121	124	125	127	128	130	131	126.6
1962	115	116	117	118	120	125	127	119.7
1963	118	121	122	123	124	126	127	123.0
1964	115	116	122	123	124	125	126	121.6
1965	120	121	122	123	124	126	127	123.3
1966	115	116	122	123	124	125	126	121.6
1967	120	121	123	125	126	130	132	125.3
1968	116	121	122	123	125	126	127	122.9
1969	116	117	120	121	122	123	124	120.4
1970	115	116	117	118	119	121	122	118.3
1971	115	124	125	127	128	129	130	125.4
1972	119	122	123	124	125	129	130	124.6
1973	115	116	117	118	123	125	126	120.0
1974	115	116	117	118	120	121	122	118.4
1975	120	122	123	125	126	127	128	124.4
1976	122	124	125	129	130	132	133	127.9
1977	120	121	122	123	126	127	128	123.9
1978	118	119	120	121	122	123	124	121.0
1984	121	122	123	124	126	127	128	124.4
1985	115	116	117	118	119	120	121	118.0
1986	117	119	121	122	123	124	125	121.6
1987	115	116	117	118	119	120	121	118.0
1988	120	121	122	123	124	125	126	123.0
1989	116	117	118	119	120	121	123	119.1
1990	115	116	117	118	119	120	121	118.0
Mean								122.88
Std. dev.								5.03

* C/S dates were planted to corn after soybeans.
C/C dates were planted to corn after corn.
SPLIT dates were split between corn after soybeans and corn after corn.

Table F.2 Soybean Planting Dates, MB Plow, 100% Fall Plowed

Year	P1*	P2	P3	P4	Mean
1953	138	139	140	143	140.0
1954	134	135	136	137	135.5
1955	127	128	132	133	130.0
1956	147	148	149	150	148.5
1957	127	128	136	137	132.0
1958	129	130	131	132	130.5
1959	129	130	132	133	131.0
1960	154	155	157	158	156.0
1961	133	134	135	136	134.5
1962	129	130	131	133	130.8
1963	132	133	134	135	133.5
1964	130	131	138	140	134.8
1965	129	130	131	132	130.5
1966	140	141	142	143	141.5
1967	135	136	137	138	136.5
1968	131	132	133	135	132.8
1969	126	132	135	148	135.3
1970	124	125	126	127	125.5
1971	133	134	135	136	134.5
1972	132	133	136	137	134.5
1973	131	132	133	134	132.5
1974	124	134	145	146	137.3
1975	133	134	135	136	134.5
1976	135	139	140	141	138.8
1977	130	131	132	133	131.5
1978	131	137	139	140	136.8
1984	130	136	137	138	135.3
1985	123	124	127	128	125.5
1986	127	128	129	130	128.5
1987	124	125	126	127	125.5
1988	128	129	132	134	130.8
1989	125	131	136	137	132.3
1990	123	126	127	128	126.0
Mean					134.03
Std. dev.					6.81

* P1 through P4 are the first through fourth days of soybean planting.

Table F.3 NH3 Application Dates, MB Plow, 100% Fall Plowed

Year	C/S*	C/S	C/S	SPLIT*	C/C*	C/C	C/C	Mean
1953	144	145	147	148	149	151	152	148.0
1954	142	143	144	145	146	148	150	145.4
1955	134	135	136	137	138	140	141	137.3
1956	145	151	152	153	155	156	157	152.7
1957	142	144	146	147	148	149	150	146.6
1958	139	140	141	143	144	145	146	142.6
1959	135	136	137	138	140	142	144	138.9
1960	144	145	146	147	149	151	152	147.7
1961	139	140	141	142	143	144	145	142.0
1962	134	135	136	137	138	139	140	137.0
1963	136	139	140	141	142	143	144	140.7
1964	135	137	141	142	143	144	145	141.0
1965	134	137	138	140	141	142	143	139.3
1966	145	146	147	148	149	150	151	148.0
1967	147	148	149	150	151	152	153	150.0
1968	137	138	140	141	142	143	144	140.7
1969	136	140	141	143	144	146	147	142.4
1970	128	129	130	131	137	138	139	133.1
1971	138	140	141	142	143	147	148	142.7
1972	138	139	140	141	142	143	144	141.0
1973	135	136	137	138	139	140	141	138.0
1974	130	139	140	141	142	143	144	139.9
1975	137	138	139	140	143	144	145	140.9
1976	142	143	144	145	146	147	148	145.0
1977	136	137	139	140	141	142	143	139.7
1978	142	143	144	145	146	147	148	145.0
1984	142	152	153	154	155	156	157	152.7
1985	130	131	132	133	134	136	137	133.3
1986	131	134	142	143	144	145	146	140.7
1987	134	135	136	137	140	141	142	137.9
1988	135	136	138	139	140	141	142	138.7
1989	142	143	144	146	147	148	149	145.6
1990	131	141	142	143	146	147	148	142.6
Mean								142.33
Std. dev.								5.63

* NH_3 applied to corn after soybeans on C/S dates.
NH_3 applied to corn after corn on C/C dates.
NH_3 applied to both corn after soybeans and corn after corn on SPLIT dates.

Table F.4 Corn Planting Dates, MB Plow, 70% Fall Plowed

Year	C/S*	C/S	C/S	SPLIT*	C/C*	C/C	C/C	Mean
1953	125	126	129	130	131	134	135	130.0
1954	123	124	125	133	134	135	136	130.0
1955	118	119	120	121	123	124	125	121.4
1956	121	134	138	139	140	141	143	136.6
1957	119	120	121	122	123	124	125	122.0
1958	121	122	123	124	125	126	127	124.0
1959	121	122	123	124	125	126	127	124.0
1960	119	123	124	125	134	135	136	128.0
1961	121	124	125	127	128	130	131	126.6
1962	115	116	117	118	120	125	127	119.7
1963	118	121	122	123	124	126	127	123.0
1964	115	116	122	123	124	125	126	121.6
1965	121	122	123	124	126	127	128	124.4
1966	115	116	122	123	124	125	126	121.6
1967	120	121	123	125	126	130	132	125.3
1968	116	121	122	123	125	126	127	122.9
1969	120	121	122	123	124	125	126	123.0
1970	117	118	119	121	122	123	124	120.6
1971	124	125	127	128	129	130	131	127.7
1972	119	122	123	124	125	129	130	124.6
1973	115	116	117	118	123	125	126	120.0
1974	115	116	117	118	120	121	122	118.4
1975	126	127	128	129	130	131	133	129.1
1976	122	124	125	129	130	132	133	127.9
1977	120	121	122	123	126	127	128	123.9
1978	118	119	120	121	122	123	124	121.0
1984	121	122	123	124	126	127	128	124.4
1985	115	116	117	118	119	120	121	118.0
1986	117	119	121	122	123	124	125	121.6
1987	115	116	117	118	119	120	121	118.0
1988	120	121	122	123	124	125	126	123.0
1989	116	117	118	119	120	121	123	119.1
1990	115	116	117	118	119	120	121	118.0
Mean								123.61
Std. dev.								5.29

* C/S dates were planted to corn after soybeans.
C/C dates were planted to corn after corn.
SPLIT dates were split between corn after soybeans and corn after corn.

Table F.5 Soybean Planting Dates, MB Plow, 70% Fall Plowed

Year	P1*	P2	P3	P4	Mean
1953	138	139	140	143	140.0
1954	138	139	140	141	139.5
1955	127	128	132	133	130.0
1956	147	148	149	150	148.5
1957	127	128	136	137	132.0
1958	129	130	131	132	130.5
1959	129	130	132	133	131.0
1960	159	160	161	162	160.5
1961	133	134	135	136	134.5
1962	129	130	131	133	130.8
1963	132	133	134	135	133.5
1964	130	131	138	140	134.8
1965	133	134	137	138	135.5
1966	140	141	142	143	141.5
1967	136	137	138	139	137.5
1968	131	132	133	135	132.8
1969	136	150	151	158	148.8
1970	130	131	140	147	137.0
1971	133	134	135	136	134.5
1972	132	133	136	137	134.5
1973	131	132	133	134	132.5
1974	146	147	150	151	148.5
1975	138	139	140	143	140.0
1976	135	139	140	141	138.8
1977	130	131	132	133	131.5
1978	137	147	148	149	145.3
1984	136	137	138	142	138.3
1985	123	124	127	128	125.5
1986	127	128	129	130	128.5
1987	124	125	126	127	125.5
1988	128	129	132	134	130.8
1989	131	136	137	138	135.5
1990	127	128	131	150	134.0
Mean					136.00
Std. dev.					7.52

* P1 through P4 are the first through fourth days of soybean planting.

Table F.6 NH3 Application Dates, MB Plow, 70% Fall Plowed

Year	C/S*	C/S	C/S	SPLIT*	C/C*	C/C	C/C	Mean
1953	144	145	147	148	149	151	152	148.0
1954	143	144	145	150	156	157	158	150.4
1955	134	135	136	137	138	140	141	137.3
1956	145	151	152	153	155	156	157	152.7
1957	142	144	146	147	148	149	150	146.6
1958	139	140	141	143	144	145	146	142.6
1959	135	136	137	138	140	142	144	138.9
1960	144	145	146	147	155	157	158	150.3
1961	139	140	141	142	143	144	145	142.0
1962	134	135	136	137	138	139	140	137.0
1963	136	139	140	141	142	143	144	140.7
1964	135	137	141	142	143	144	145	141.0
1965	141	142	147	148	149	150	151	146.9
1966	145	146	147	148	149	150	151	148.0
1967	147	148	149	150	151	152	153	150.0
1968	137	138	140	141	142	143	144	140.7
1969	141	143	144	146	147	148	149	145.4
1970	137	138	139	141	142	143	146	140.9
1971	138	140	141	142	143	147	148	142.7
1972	138	139	140	141	142	143	144	141.0
1973	135	136	137	138	139	140	141	138.0
1974	139	140	141	142	143	144	145	142.0
1975	144	145	147	148	149	152	154	148.4
1976	142	143	144	145	146	147	148	145.0
1977	136	137	139	140	141	142	143	139.7
1978	142	143	144	145	146	147	148	145.0
1984	152	153	154	155	156	157	158	155.0
1985	130	131	132	133	134	136	137	133.3
1986	131	134	142	143	144	145	146	140.7
1987	134	135	136	137	140	141	142	137.9
1988	135	136	138	139	140	141	142	138.7
1989	142	143	144	146	147	148	149	145.6
1990	141	142	143	146	147	148	149	145.1
Mean								143.68
Std. dev.								5.81

* NH_3 applied to corn after soybeans on C/S dates.
NH_3 applied to corn after corn on C/C dates.
NH_3 applied to both corn after soybeans and corn after corn on SPLIT dates.

Table F.7 Corn Planting Dates, MB Plow, 45% Fall Plowed

Year	C/S*	C/S	C/S	SPLIT*	C/C*	C/C	C/C	Mean
1953	125	126	129	130	131	134	135	130.0
1954	133	134	135	136	137	138	139	136.0
1955	118	119	120	121	123	124	125	121.4
1956	121	134	138	139	140	141	143	136.6
1957	119	120	121	122	123	124	125	122.0
1958	121	122	123	124	125	126	127	124.0
1959	121	122	123	124	125	126	127	124.0
1960	134	135	144	145	146	147	149	142.9
1961	121	124	125	127	128	130	131	126.6
1962	115	116	117	118	120	125	127	119.7
1963	118	121	122	123	124	126	127	123.0
1964	115	116	122	123	124	125	126	121.6
1965	126	127	128	129	130	131	132	129.0
1966	115	116	122	123	124	125	126	121.6
1967	125	126	130	132	133	134	135	130.7
1968	116	121	122	123	125	126	127	122.9
1969	124	125	126	132	135	136	140	131.1
1970	122	123	124	125	126	127	128	125.0
1971	124	125	127	128	129	130	131	127.7
1972	122	123	124	125	129	130	132	126.4
1973	115	116	117	118	123	125	126	120.0
1974	120	121	122	124	127	130	134	125.4
1975	130	131	133	134	135	136	137	133.7
1976	122	124	125	129	130	132	133	127.9
1977	120	121	122	123	126	127	128	123.9
1978	122	123	124	127	128	130	137	127.3
1984	126	127	128	129	131	133	135	129.9
1985	115	116	117	118	119	120	121	118.0
1986	117	119	121	122	123	124	125	121.6
1987	115	116	117	118	119	120	121	118.0
1988	120	121	122	123	124	125	126	123.0
1989	118	119	120	121	123	124	125	121.4
1990	118	119	120	121	122	123	126	121.3
Mean								125.86
Std. dev.								6.59

* C/S dates were planted to corn after soybeans.
C/C dates were planted to corn after corn.
SPLIT dates were split between corn after soybeans and corn after corn.

Table F.8 Soybean Planting Dates, MB Plow, 45% Fall Plowed

Year	P1*	P2	P3	P4	Mean
1953	139	140	143	144	141.5
1954	141	142	143	144	142.5
1955	132	133	134	135	133.5
1956	149	150	151	152	150.5
1957	136	137	151	153	144.3
1958	129	130	131	132	130.5
1959	134	135	136	137	135.5
1960	160	161	162	170	163.3
1961	133	134	135	136	134.5
1962	129	130	131	133	130.8
1963	132	133	134	135	133.5
1964	130	131	138	140	134.8
1965	141	142	156	157	149.0
1966	140	141	142	143	141.5
1967	140	141	143	145	142.3
1968	131	132	133	135	132.8
1969	161	162	163	165	162.8
1970	139	140	141	142	140.5
1971	133	134	135	136	134.5
1972	140	141	142	143	141.5
1973	131	132	133	134	132.5
1974	153	154	155	156	154.5
1975	145	147	148	149	147.3
1976	135	139	140	141	138.8
1977	133	134	135	136	134.5
1978	150	151	152	153	151.5
1984	162	163	164	166	163.8
1985	123	124	127	128	125.5
1986	127	128	129	130	128.5
1987	124	125	126	127	125.5
1988	129	132	134	135	132.5
1989	131	136	137	138	135.5
1990	152	153	154	155	153.5
Mean					140.71
Std. dev.					10.68

* P1 through P4 are the first through fourth days of soybean planting.

Table F.9 NH3 Application Dates, MB Plow, 45% Fall Plowed

Year	C/S*	C/S	C/S	SPLIT*	C/C*	C/C	C/C	Mean
1953	145	147	148	149	151	152	153	149.3
1954	148	150	156	157	158	159	160	155.4
1955	137	138	140	141	143	146	147	141.7
1956	144	153	155	156	157	158	160	154.7
1957	142	144	146	147	148	149	150	146.6
1958	139	140	141	143	144	145	146	142.6
1959	140	142	144	145	147	148	149	145.0
1960	158	159	171	172	174	176	177	169.6
1961	139	140	141	142	143	144	145	142.0
1962	134	135	136	137	138	139	140	137.0
1963	136	139	140	141	142	143	144	140.7
1964	135	137	141	142	143	144	145	141.0
1965	147	148	149	150	151	152	155	150.3
1966	135	139	145	146	147	148	149	144.1
1967	146	147	148	149	150	151	152	149.0
1968	137	138	140	141	142	143	144	140.7
1969	148	149	150	151	158	159	160	153.6
1970	143	146	147	148	149	151	152	148.0
1971	138	140	141	142	143	147	148	142.7
1972	144	145	146	147	148	152	153	147.9
1973	135	136	137	138	139	140	141	138.0
1974	144	145	146	147	150	151	152	147.9
1975	152	154	157	158	159	160	161	157.3
1976	142	143	144	145	146	147	148	145.0
1977	140	141	142	143	145	146	147	143.4
1978	144	145	146	147	148	149	154	147.6
1984	153	154	155	156	157	158	160	156.1
1985	130	131	132	133	134	136	137	133.3
1986	131	134	142	143	144	145	146	140.7
1987	134	135	136	137	140	141	142	137.9
1988	138	139	140	141	142	143	144	141.0
1989	142	143	144	146	147	148	149	145.6
1990	143	146	147	148	149	150	151	147.7
Mean								146.16
Std. dev.								7.78

* NH_3 applied to corn after soybeans on C/S dates.
NH_3 applied to corn after corn on C/C dates.
NH_3 applied to both corn after soybeans and corn after corn on SPLIT dates.

Table F.10 Corn Planting Dates, No-Till System*

Year								Mean
1953	125	126	129	130	131	**135**	138	130.6
1954	120	121	123	124	125	126	**134**	124.7
1955	117	118	119	120	121	**123**	124	120.3
1956	134	138	139	140	141	**143**	144	139.9
1957	119	120	121	122	**123**	124	125	122.0
1958	115	122	123	124	125	**126**	127	123.1
1959	121	122	123	124	125	**126**	127	124.0
1960	118	119	123	124	125	135	136	125.7
1961	125	127	128	130	131	132	**133**	129.4
1962	115	116	117	118	120	125	**129**	120.0
1963	121	122	123	124	126	127	**128**	124.4
1964	115	116	122	123	124	**125**	126	121.6
1965	120	121	122	123	124	**126**	127	123.3
1966	115	116	125	126	127	**128**	129	123.7
1967	120	121	123	125	126	**133**	134	126.0
1968	116	121	122	123	125	**126**	127	122.9
1969	117	120	121	122	123	**124**	125	121.7
1970	115	116	117	118	119	**121**	122	118.3
1971	115	124	125	127	128	**129**	130	125.4
1972	122	123	124	**125**	129	130	131	126.3
1973	115	116	117	**118**	123	125	126	120.0
1974	115	116	117	118	120	**121**	122	118.4
1975	120	122	123	125	126	127	**128**	124.4
1976	124	130	132	133	134	**135**	139	132.4
1977	120	121	122	123	126	**127**	128	123.9
1978	119	120	121	122	123	**124**	131	122.9
1984	122	123	124	**126**	127	128	129	125.6
1985	115	116	117	**118**	119	120	121	118.0
1986	117	119	121	**122**	123	124	125	121.6
1987	115	116	117	**118**	119	120	121	118.0
1988	119	120	121	122	123	**124**	125	122.0
1989	116	117	118	**119**	120	121	123	119.1
1990	115	116	117	**118**	119	120	121	118.0
Mean								123.55
Std. dev.								5.67

* Underlined dates are for corn after soybeans. Dates in bold print are split between corn after soybeans and corn after corn. Remaining dates are for corn after corn.

Table F.11 Soybean Planting Dates, No-Till System

Year	P1*	P2	P3	P4	Mean
1953	140	143	144	154	145.3
1954	136	137	138	139	137.5
1955	126	127	128	131	128.0
1956	147	148	149	150	148.5
1957	127	128	136	137	132.0
1958	130	131	132	133	131.5
1959	129	130	132	133	131.0
1960	151	152	157	158	154.5
1961	135	136	137	139	136.8
1962	131	133	134	135	133.3
1963	132	134	135	136	134.3
1964	131	143	144	145	140.8
1965	129	130	131	132	130.5
1966	139	140	141	142	140.5
1967	137	138	139	140	138.5
1968	129	130	131	132	130.5
1969	131	132	135	136	133.5
1970	124	125	126	127	125.5
1971	133	134	135	136	134.5
1972	133	137	138	139	136.8
1973	131	132	133	134	132.5
1974	124	140	141	142	136.8
1975	130	131	135	136	133.0
1976	141	142	143	145	142.8
1977	130	131	132	133	131.5
1978	137	139	140	144	140.0
1984	137	138	157	158	147.5
1985	123	124	127	128	125.5
1986	127	128	129	130	128.5
1987	124	125	126	127	125.5
1988	127	128	129	132	129.0
1989	125	136	137	138	134.0
1990	123	127	128	150	132.0
Mean					135.21
Std. dev.					7.70

* P1 through P4 are the first through fourth days of soybean planting.

Table F.12 NH3 Application Dates, No-Till System

Year								Mean
1953	145	147	148	149	151	152	153	149.3
1954	145	146	148	150	156	157	158	151.4
1955	132	133	134	135	136	137	138	135.0
1956	151	152	153	155	156	157	158	154.6
1957	142	144	146	147	148	149	150	146.6
1958	139	140	141	143	144	145	146	142.6
1959	135	136	137	138	140	142	144	138.9
1960	144	145	146	147	149	154	155	148.6
1961	140	141	142	143	144	145	147	143.1
1962	136	137	138	139	141	142	143	139.4
1963	139	140	141	142	143	144	145	142.0
1964	130	135	137	138	140	141	142	137.6
1965	133	134	137	138	140	141	142	137.9
1966	146	147	148	149	150	151	152	149.0
1967	145	146	147	148	149	150	151	148.0
1968	137	138	140	141	142	143	144	140.7
1969	133	134	140	141	143	144	146	140.1
1970	128	129	130	131	137	138	139	133.1
1971	137	138	140	141	142	143	147	141.1
1972	140	141	142	143	144	145	146	143.0
1973	135	136	137	138	139	140	141	138.0
1974	130	134	139	143	144	145	146	140.1
1975	137	138	139	140	143	144	145	140.9
1976	144	146	147	148	153	154	155	149.6
1977	137	139	140	141	142	143	145	141.0
1978	142	143	145	146	147	148	149	145.7
1984	145	148	152	153	154	155	156	151.9
1985	129	130	131	132	133	134	136	132.1
1986	131	132	133	134	143	144	145	137.4
1987	133	134	135	136	137	140	141	136.6
1988	134	135	136	139	140	141	142	138.1
1989	141	142	143	144	147	148	149	144.9
1990	142	143	147	148	141	146	149	145.1

Mean								142.52
Std. dev.								6.38

Table F.13 Corn Yield Results (BU/A), 100% Fall Plowed

Year	C/S	C/S	C/S	SPLIT	SPLIT	C/C	C/C	C/C	Mean
1953	105.2	103.6	109.1	114.6	114.7	116.4	120.3	120.4	112.81
1954	70.9	79.3	66.2	73.9	73.3	64.3	64.2	64.7	69.03
1955	110.7	115.6	116.4	99.2	97.9	83.4	99.6	102.5	103.82
1956	122.2	116.8	108.9	108.9	108.5	104.8	133.7	129.8	117.84
1957	165.8	150.1	141.9	140.0	139.4	139.4	139.1	118.5	142.07
1958	159.9	159.6	161.7	156.1	154.1	148.1	147.6	147.6	154.23
1959	147.2	141.8	145.9	134.4	134.4	128.9	126.0	116.8	134.43
1960	102.4	103.5	98.7	98.5	97.9	104.5	97.7	97.6	100.37
1961	106.3	101.2	105.5	100.8	100.9	101.0	98.4	97.2	101.49
1962	74.1	72.6	68.9	64.2	63.5	51.9	51.3	53.2	62.26
1963	129.3	126.4	127.1	128.9	125.7	123.9	129.1	133.8	128.13
1964	104.6	98.5	111.8	108.8	109.2	100.9	104.5	94.0	103.33
1965	50.3	52.7	50.7	47.9	48.2	48.4	41.6	44.1	47.98
1966	82.0	82.0	93.9	93.9	94.3	80.3	80.2	80.3	84.69
1967	48.1	49.1	48.5	48.4	48.4	48.4	49.5	49.5	48.79
1968	138.4	141.2	134.1	139.7	139.7	139.3	139.5	134.7	138.13
1969	168.0	166.8	157.2	161.8	162.0	163.9	162.7	167.9	164.06
1970	161.8	162.4	156.5	152.5	152.7	150.4	173.5	183.1	162.90
1971	75.5	75.7	75.5	77.8	77.5	76.5	75.2	78.1	76.31
1972	94.3	95.8	92.4	96.5	96.2	99.0	98.8	102.9	97.08
1973	55.0	53.9	52.4	52.4	52.3	54.9	64.2	58.1	55.84
1974	46.7	53.8	52.3	53.0	53.3	59.1	58.0	56.1	54.16
1975	109.6	109.6	103.4	105.8	105.6	110.2	100.2	109.4	106.87
1976	59.5	68.0	68.2	66.3	66.6	65.3	63.9	48.7	62.86
1977	128.4	130.9	137.3	140.4	141.0	150.0	138.1	152.1	139.64
1978	78.8	82.1	83.5	83.8	83.6	81.6	84.0	83.9	82.51
1984	74.8	59.1	75.7	75.8	75.3	81.2	61.8	61.9	70.01
1985	177.0	177.2	181.0	175.7	175.7	174.8	168.5	170.5	174.96
1986	218.3	215.5	218.1	214.0	210.4	213.4	213.3	206.9	213.96
1987	117.8	102.9	97.0	97.5	97.4	99.2	102.2	102.2	102.68
1988	64.8	68.4	69.1	72.6	72.4	93.3	78.2	97.0	77.61
1989	165.4	163.0	162.9	163.0	162.3	162.8	162.8	154.2	161.96
1990	173.7	180.9	183.5	179.1	178.7	178.6	178.9	177.0	178.79
Mean									110.05
Std. dev.									42.74

* C/S dates were planted to corn after soybeans.
C/C dates were planted to corn after corn.
SPLIT dates were split between corn after soybeans and corn after corn.

Table F.14 Soybean Yield Results (BU/A), 100% Fall Plowed

Year	P1	P2	P3	P4	Mean
1953	27.7	27.7	27.5	27.6	27.63
1954	17.4	17.4	17.5	17.0	17.33
1955	33.5	33.5	33.6	33.6	33.55
1956	47.9	47.9	48.0	48.2	48.00
1957	32.0	31.6	27.6	27.6	29.70
1958	43.7	43.6	43.5	43.0	43.45
1959	56.5	56.5	58.3	58.2	57.38
1960	39.7	40.7	33.7	32.9	36.75
1961	47.6	47.6	47.9	48.5	47.90
1962	20.4	21.2	21.9	22.0	21.28
1963	42.1	42.2	42.4	42.3	42.25
1964	28.8	28.9	27.9	30.2	28.95
1965	21.8	21.8	22.3	22.5	21.38
1966	20.6	20.7	21.2	21.3	20.95
1967	19.8	19.7	19.6	19.7	19.70
1968	29.6	29.6	29.9	30.9	30.00
1969	39.5	38.5	38.3	36.1	38.10
1970	41.5	41.4	40.8	40.8	41.13
1971	17.3	17.3	17.5	17.6	17.43
1972	36.2	37.8	40.3	41.8	39.03
1973	17.6	16.8	16.8	16.9	17.03
1974	18.7	19.5	23.9	24.2	21.58
1975	34.9	34.8	34.7	35.9	35.08
1976	15.4	15.5	15.5	17.5	15.98
1977	40.9	40.8	40.7	40.4	40.70
1978	18.0	20.0	21.8	21.9	20.43
1984	27.5	28.5	28.5	28.7	28.30
1985	41.9	42.0	43.1	43.2	42.55
1986	59.5	59.0	59.0	58.3	58.95
1987	47.2	47.3	47.8	49.5	47.95
1988	49.1	49.2	52.5	52.5	50.83
1989	45.5	45.5	45.1	45.9	45.50
1990	39.5	39.4	39.4	39.7	39.50
Mean					34.13
Std. dev.					12.25

* P1 through P4 are the first through fourth days of soybean planting.

Table F.15 Corn Yield Results (BU/A), 70% Fall Plowed

	C/S	C/S	C/S	SPLIT	SPLIT	C/C	C/C	C/C	Mean
1953	105.2	103.6	109.1	114.6	114.7	116.4	120.3	120.4	112.81
1954	64.1	64.1	64.1	65.3	65.7	62.3	61.8	61.4	63.33
1955	110.7	115.6	116.4	99.2	97.9	83.4	99.6	102.5	103.82
1956	122.2	116.8	108.9	108.9	108.5	104.8	133.7	129.8	117.84
1957	165.8	150.1	141.9	140.0	139.4	139.4	139.1	118.5	142.07
1958	159.9	159.6	161.7	156.1	154.1	148.1	147.6	147.6	154.23
1959	147.2	141.8	145.9	134.4	134.4	128.9	126.0	116.8	134.43
1960	103.5	98.7	98.5	104.8	104.5	97.8	97.6	97.9	99.81
1961	106.3	101.2	105.5	100.8	100.9	101.0	98.4	97.2	101.49
1962	74.1	72.6	68.9	64.2	63.5	51.9	51.3	53.2	62.26
1963	129.3	126.4	127.1	128.9	125.7	123.9	129.1	133.8	128.13
1964	104.6	98.5	111.8	108.8	109.2	100.9	104.5	94.0	103.33
1965	52.5	50.1	47.8	48.6	48.3	48.4	49.5	49.6	49.48
1966	82.0	82.0	93.9	93.9	94.3	80.3	80.2	80.3	84.69
1967	48.2	49.1	48.6	48.4	48.3	48.4	49.5	49.6	48.82
1968	138.4	141.2	134.1	139.7	139.7	139.3	139.5	134.7	138.13
1969	157.2	161.8	163.8	162.9	162.7	167.9	164.2	162.7	162.91
1970	156.6	152.4	150.1	173.1	173.5	182.9	188.0	154.6	165.41
1971	75.7	75.4	77.6	75.6	75.8	75.2	78.1	76.3	76.29
1972	94.3	95.8	92.4	96.5	96.3	99.0	98.8	103.0	97.10
1973	55.0	53.9	52.4	52.4	52.3	54.9	64.2	58.1	55.84
1974	54.4	53.8	52.3	53.0	53.3	59.1	58.0	56.1	55.26
1975	110.3	100.4	110.6	110.8	110.0	105.1	108.3	101.3	106.63
1976	59.5	68.0	68.2	66.3	66.6	65.3	63.9	48.7	62.86
1977	128.4	130.9	137.3	140.4	141.0	150.0	138.1	152.1	139.64
1978	78.9	82.5	83.6	83.8	83.6	81.6	83.9	83.9	82.59
1984	73.7	59.1	75.8	75.8	75.4	80.9	61.9	62.0	69.86
1985	177.0	177.2	181.0	175.7	175.7	174.8	168.5	170.5	174.96
1986	218.3	215.5	218.1	214.0	210.4	213.4	213.3	206.9	213.96
1987	117.8	102.9	97.0	97.5	97.4	99.2	102.2	102.2	102.68
1988	64.8	68.4	69.1	72.6	72.4	93.3	78.2	97.0	77.61
1989	165.4	163.0	162.9	163.0	162.3	162.8	162.8	154.2	161.96
1990	171.4	180.9	183.5	179.2	178.7	178.6	178.9	177.0	178.46
Mean									109.96
Std. dev.									42.98

* C/S dates were planted to corn after soybeans.
C/C dates were planted to corn after corn.
SPLIT dates were split between corn after soybeans and corn after corn.

Table F.16 Soybean Yield Results (BU/A), 70% Fall Plowed

Year	P1	P2	P3	P4	Mean
1953	27.7	27.7	27.5	27.6	27.63
1954	17.0	16.6	16.6	16.1	16.58
1955	33.5	33.5	33.6	33.6	33.55
1956	47.9	47.9	48.0	48.2	48.00
1957	32.0	31.6	27.6	27.6	29.70
1958	43.7	43.6	43.5	43.0	43.45
1959	56.5	56.5	58.3	58.2	57.38
1960	32.8	36.7	36.8	39.4	36.43
1961	47.6	47.6	47.9	48.5	47.90
1962	20.4	21.2	21.9	22.0	21.28
1963	42.1	42.2	42.4	42.3	42.25
1964	28.8	28.9	27.9	30.2	28.95
1965	22.1	23.1	23.7	23.6	23.13
1966	20.6	20.7	21.2	21.3	20.95
1967	19.7	19.6	19.7	20.1	19.78
1968	29.6	29.6	29.9	30.9	30.00
1969	38.3	31.8	31.3	29.4	32.70
1970	41.1	41.1	37.6	35.6	38.85
1971	17.3	17.3	17.5	17.6	17.43
1972	36.2	37.8	40.3	41.8	39.03
1973	17.6	16.8	16.8	16.9	17.03
1974	24.2	24.7	26.2	26.7	25.45
1975	36.5	37.6	37.5	40.7	38.08
1976	15.4	15.5	15.5	17.5	15.98
1977	40.9	40.8	40.7	40.4	40.70
1978	20.0	27.3	28.2	28.1	25.90
1984	28.5	28.5	28.7	29.2	28.73
1985	41.9	42.0	43.1	43.2	42.55
1986	59.5	59.0	59.0	58.3	58.95
1987	47.2	47.3	47.8	49.5	47.95
1988	49.1	49.2	52.5	52.5	50.83
1989	45.5	45.1	45.9	46.4	45.73
1990	39.4	39.7	40.0	46.7	41.45
Mean					34.37
Std. dev.					12.22

* P1 through P4 are the first through fourth days of soybean planting.

Table F.17 Corn Yield Results (BU/A), 45% Fall Plowed

Year	C/S	C/S	C/S	SPLIT	SPLIT	C/C	C/C	C/C	Mean
1953	105.2	103.6	109.1	114.6	114.7	116.4	120.3	120.4	112.81
1954	65.3	62.2	61.6	61.5	61.3	53.0	61.4	61.4	60.90
1955	110.7	115.6	116.4	99.1	97.9	83.3	99.4	102.4	103.76
1956	122.2	116.9	108.9	108.9	108.5	104.8	102.7	100.7	109.27
1957	165.8	150.1	141.9	140.0	139.4	139.4	139.1	118.5	142.07
1958	159.9	159.6	161.7	156.1	154.1	148.1	147.6	147.6	154.23
1959	147.2	141.7	145.4	134.1	133.9	128.9	126.1	116.8	134.30
1960	98.0	97.7	84.7	78.6	78.7	78.1	66.9	66.1	81.45
1961	106.3	101.2	105.5	100.8	100.9	101.0	98.4	97.2	101.49
1962	74.1	72.6	68.9	64.2	63.5	51.9	51.3	53.2	62.26
1963	129.3	126.4	127.1	128.9	125.7	123.9	129.1	133.8	128.13
1964	104.6	98.5	111.8	108.8	109.2	100.9	104.5	94.0	103.33
1965	41.3	43.7	45.6	39.0	38.8	49.2	52.2	34.9	43.69
1966	82.0	82.0	93.9	93.9	94.3	80.3	80.2	80.4	84.70
1967	48.4	48.4	49.5	49.5	49.6	50.3	49.2	49.3	49.24
1968	138.4	141.2	134.1	139.7	139.7	139.3	139.5	134.7	138.13
1969	167.4	164.1	160.8	163.5	164.0	157.4	164.7	155.5	161.95
1970	182.4	187.4	153.9	154.1	154.2	154.4	195.0	189.9	173.88
1971	75.7	75.4	77.6	75.6	75.8	75.2	78.1	76.3	76.29
1972	95.9	92.4	96.2	99.2	99.1	98.8	103.0	101.8	98.18
1973	55.0	53.9	52.4	52.4	52.3	54.9	64.2	58.1	55.84
1974	59.8	58.1	56.2	55.5	55.9	55.6	60.4	59.5	57.90
1975	108.9	109.7	103.4	106.4	105.8	109.6	100.8	109.6	106.87
1976	59.5	68.0	68.2	66.3	66.6	65.3	63.9	48.7	62.86
1977	128.5	130.9	137.3	140.5	141.0	150.0	138.6	152.1	139.74
1978	81.1	84.1	84.1	84.9	84.8	86.8	89.3	84.4	84.95
1984	81.4	61.6	61.6	68.6	68.3	86.9	69.3	93.9	74.74
1985	177.0	177.2	181.0	175.7	175.7	174.8	168.5	170.5	174.96
1986	218.3	215.5	218.1	214.0	210.4	213.4	213.3	206.9	213.96
1987	117.8	102.9	97.0	97.5	97.4	99.2	102.2	102.2	102.68
1988	64.4	68.0	69.1	72.6	72.4	93.3	78.2	97.0	77.50
1989	162.8	162.7	162.7	162.9	162.8	154.2	154.2	154.2	159.09
1990	179.1	178.8	179.0	177.0	177.0	173.6	173.6	158.4	174.21
Mean									109.25
Std. dev.									43.35

* C/S dates were planted to corn after soybeans.
C/C dates were planted to corn after corn.
SPLIT dates were split between corn after soybeans and corn after corn.

Table F.18 Soybean Yield Results (BU/A), 45% Fall Plowed

Year	P1	P2	P3	P4	Mean
1953	27.7	27.5	27.6	27.6	27.60
1954	16.1	16.1	16.2	16.4	16.20
1955	33.6	33.6	33.4	33.1	33.43
1956	48.0	48.2	48.6	48.5	48.33
1957	27.6	27.6	23.0	22.1	25.08
1958	43.7	43.6	43.5	43.0	43.45
1959	59.6	59.6	59.6	59.3	59.53
1960	24.2	25.0	25.0	25.7	24.98
1961	47.6	47.6	47.9	48.5	47.90
1962	20.4	21.2	21.9	22.0	21.28
1963	42.1	42.2	42.4	42.3	42.25
1964	28.8	28.9	27.9	30.2	28.95
1965	25.0	26.4	34.2	34.6	29.95
1966	20.6	20.7	21.2	21.3	20.95
1967	20.2	20.6	20.7	20.9	20.60
1968	29.6	29.6	29.9	30.9	30.00
1969	28.4	28.1	27.9	26.2	27.65
1970	38.0	37.6	36.9	36.2	37.18
1971	17.3	17.3	17.5	17.6	17.43
1972	42.0	43.4	44.4	45.5	43.83
1973	17.6	16.8	16.8	16.9	17.03
1974	26.8	27.5	27.5	28.5	27.58
1975	44.3	45.0	45.3	45.7	45.08
1976	15.4	15.5	15.5	17.5	15.98
1977	40.4	40.2	39.4	39.1	39.78
1978	28.3	29.0	29.7	30.1	29.28
1984	27.0	28.1	27.5	27.8	27.60
1985	41.9	42.0	43.1	43.2	42.55
1986	59.5	59.0	59.0	58.3	58.95
1987	47.2	47.3	47.8	49.5	47.95
1988	49.2	52.5	52.5	54.2	52.10
1989	45.5	45.1	45.9	46.4	45.73
1990	47.4	47.2	48.2	48.3	47.78
Mean					34.66
Std. dev.					12.50

* P1 through P4 are the first through fourth days of soybean planting.

Table F.19 Corn Yield Results (BU/A), No-Till System

Year	C/S	C/S	C/S	SPLIT	SPLIT	C/C	C/C	C/C	Mean
1953	104.5	102.0	112.6	124.8	118.1	117.7	119.6	122.8	114.38
1954	75.6	65.6	72.4	62.5	57.7	68.0	67.3	67.6	68.09
1955	108.9	110.7	102.9	98.9	106.2	110.9	97.8	109.3	106.15
1956	115.2	106.9	122.6	122.7	107.7	105.2	99.1	125.6	112.83
1957	148.4	131.7	132.7	131.8	126.4	115.4	132.4	132.1	131.69
1958	170.0	162.3	152.7	163.7	177.9	155.7	155.6	155.6	160.39
1959	140.7	143.9	125.2	126.5	125.5	134.4	126.7	126.7	131.94
1960	103.1	106.3	93.9	93.9	93.6	104.6	107.9	101.2	101.54
1961	106.7	101.1	98.1	101.1	107.2	102.3	113.8	109.6	105.11
1962	74.1	51.7	51.0	56.5	53.6	71.0	64.9	64.5	61.75
1963	130.0	129.9	135.8	135.3	141.7	135.7	136.1	136.3	134.61
1964	109.4	112.8	92.0	94.4	100.6	119.5	119.1	101.7	107.43
1965	60.3	55.6	42.1	43.9	46.9	55.1	53.0	46.7	51.17
1966	80.7	80.8	83.6	87.8	85.1	79.8	79.7	78.0	81.29
1967	54.1	49.4	48.0	48.0	49.1	47.4	48.5	48.5	49.21
1968	134.1	127.3	130.5	128.0	126.6	126.9	126.4	127.5	128.57
1969	163.0	160.6	161.4	159.9	166.3	162.4	164.8	164.7	162.86
1970	160.8	166.9	154.6	183.7	154.8	152.3	150.3	161.4	159.36
1971	76.3	75.0	79.5	78.0	85.8	81.9	81.5	83.3	79.91
1972	103.8	100.3	102.0	96.1	103.4	95.2	95.2	99.2	99.35
1973	57.1	58.6	69.7	56.4	54.3	54.2	54.6	54.6	57.74
1974	43.2	47.7	57.1	56.6	57.2	58.3	58.4	56.6	54.03
1975	99.0	109.8	106.1	106.6	111.9	123.2	114.6	118.6	111.51
1976	66.9	64.7	59.3	53.9	49.0	59.1	53.9	52.3	58.24
1977	137.4	143.8	155.8	153.0	158.9	146.3	151.9	158.7	149.98
1978	84.1	84.2	88.5	90.9	59.4	87.4	95.3	88.1	86.11
1984	86.4	67.3	67.3	90.2	92.6	94.8	95.9	68.3	81.63
1985	165.2	166.1	165.5	168.7	163.5	167.5	170.2	168.4	167.00
1986	204.5	203.9	195.3	202.4	200.9	204.4	201.0	200.0	201.54
1987	103.8	103.7	104.8	103.8	113.9	107.5	107.3	107.2	106.16
1988	69.5	69.4	78.2	77.6	101.0	76.2	77.2	78.6	76.91
1989	155.6	154.9	157.2	157.9	167.6	174.0	165.4	165.3	162.16
1990	184.3	176.5	169.1	179.4	178.5	169.7	183.0	182.9	177.78
Mean									110.25
Std. dev.									41.35

* C/S dates were planted to corn after soybeans.
C/C dates were planted to corn after corn.
SPLIT dates were split between corn after soybeans and corn after corn.

Table F.20 Soybean Yield Results (BU/A), No-Till System

Year	P1	P2	P3	P4	Mean
1953	29.4	29.1	29.0	28.0	28.88
1954	19.4	19.2	18.8	18.7	19.03
1955	35.7	35.8	36.0	36.0	35.88
1956	49.7	49.6	49.7	49.6	49.65
1957	32.2	31.6	28.0	27.7	29.88
1958	44.1	44.0	44.5	44.5	44.28
1959	58.6	60.0	59.7	60.7	59.75
1960	37.7	38.8	34.4	34.4	36.33
1961	49.3	49.2	49.8	49.3	49.40
1962	24.5	24.4	25.4	25.4	24.93
1963	43.4	43.4	43.6	43.1	43.38
1964	29.8	32.2	33.3	33.0	32.08
1965	20.4	21.0	21.5	21.4	21.08
1966	22.0	22.1	22.8	22.8	22.43
1967	20.3	20.2	20.2	20.6	20.33
1968	29.9	29.9	30.1	30.0	29.98
1969	38.8	38.4	37.5	37.0	37.93
1970	42.0	41.9	42.2	42.2	42.08
1971	19.8	19.8	19.8	19.9	19.83
1972	38.6	41.4	41.6	41.5	40.78
1973	18.2	18.2	17.5	17.5	17.85
1974	20.4	22.0	22.6	23.0	22.00
1975	37.5	38.3	38.9	38.7	38.35
1976	17.6	17.4	18.5	18.4	17.98
1977	41.4	41.3	41.3	40.6	41.15
1978	23.3	23.7	23.9	27.2	24.53
1984	29.7	29.8	29.2	28.7	29.35
1985	42.9	44.4	43.9	43.6	43.70
1986	59.4	59.1	58.9	61.4	59.70
1987	49.9	49.9	51.2	51.3	50.58
1988	51.9	52.2	52.5	54.3	52.73
1989	46.7	46.8	47.0	46.9	46.85
1990	38.9	39.1	39.1	46.7	40.95
Mean					35.56
Std. dev.					12.21

* P1 through P4 are the first through fourth days of soybean planting.

Appendix G

FORTRAN CODE FOR THE DETERMINISTIC DYNAMIC PROGRAMMING MODEL

This Appendix contains the FORTRAN code for the deterministic dynamic programming model that is used to determine optimal adoption strategies for the profit-maximizing farmer. A list of explanations for the variable names also is provided. Although the FORTRAN code was compiled and executed using Microsoft FORTRAN, Ver. 5.1, nearly all of the code follows the FORTRAN 77 standard. The only exceptions are a few statements regarding how variables are stored in computer memory. The statements or the parts of those statements that do not conform to the FORTRAN 77 standard are shown in bold print.

The listed code is for the version of the model that includes options to rent the no-till planter on a limited acreage. The version that does not include these options is identical except that the additional rental rates are not read from the input file and value functions for the additional options are not calculated.

Description of Variable Names (in order of appearance)

TITLE	Description of the run, printed on the output file.
N	Number of years in the planning horizon.
MP	Maximum age that the planter can be used.
MT	Maximum age that the tractor can be used.
IAGE1	Initial age of the conventional planter (may be 0).
IAGE2	Initial age of the no-till planter (usually is 0).
IAGE3	Initial age of the 140 HP tractor (may be 0).
IAGE4	Initial age of the 85 HP tractor (usually is 0).
CX(i), i=1,4	Cost inflation factors for the learning curve effect.
DF	Discount rate.
KX	Years of no-till experience (1 implies no experience).
PR1	Purchase price, conventional planter.
RNT1	Rental fee for the conventional planter on 600 acres.
PR2	Purchase price, no-till planter.
RNT2	Rental fee for the no-till planter on 600 acres.

PR3	Purchase price, 140 HP tractor.
PR4	Purchase price, 85 HP tractor.
RK1	Rental fee for renting no-till planter on 60 acres.
RK2	Rental fee for renting no-till planter on 120 acres.
RK3	Rental fee for renting no-till planter on 240 acres.
KPI	Initial age of whichever planter is owned.
KTI	Initial age of whichever tractor is owned.
MPP1	Age at which planter must be replaced.
MTP2	Age at which tractor must be replaced.
MPOL	Last year that the policy variable is determined.
A	1/(1+discount factor)
OWN, OWNP, OWNT	Ownership state markers used to control printouts.
R1	Conventional tillage revenue on 600 acres minus Subtotal 1 variable costs (Table 4.10).
R2	Conventional tillage revenue on 600 acres minus Subtotal 1 variable costs (Table 4.10).
OB	Lower bound on years in detailed printouts.
OT	Upper bound on years in detailed printouts.
CN1	Repair costs for a new conventional planter plus Subtotal 2 variable costs on 600 acres.
CN2	Repair costs for a new no-till planter plus Subtotal 2 variable costs on 600 acres.
CN3	Repair costs for a new 140 HP tractor.
CN4	Repair Cost for a new 85 HP tractor.
C1(K)	Repair costs for a conventional planter of age K. plus Subtotal 2 variable costs on 600 acres.
C2(K)	Repair costs for a no-till planter of age K. plus Subtotal 2 variable costs on 600 acres.
T1(K)	Trade-in value for a conventional planter of age K.
T2(K)	Trade-in value for a no-till planter of age K.
C3(K)	Repair costs for 400 hours use of a 140 HP tractor of age K.
C4(K)	Repair costs for 400 hours use of an 85 HP tractor of age K.
T3(K)	Trade-in value for a 140 HP tractor of age K.
T4(K)	Trade-in value for an 85 HP tractor of age K.
J	Counter variable for years of experience.
KT	Counter variable for tractor age (in 400 hour units).
KP	Counter variable for planter age (in years).
II, IM1, JM1	Counters used to control the backwards recursion.
IHI, JHI	Bounds used to control the backwards recursion.
I	Year in the planning horizon.
PL3	Optimal policy for owning the large tractor only.
VL3	Current-period value function for owning the large tractor only.
PL4	Optimal policy for owning the small tractor only.
VL4	Current-period value function for owning the small tractor only.
P1	Optimal policy for owning the large tractor and conventional planter.
P2	Optimal policy for owning the large tractor and no-till planter.

P4	Optimal policy for owning the small tractor and no-till planter.
VLN3	Next-period value function for owning the large tractor only.
VLN4	Next-period value function for owning the small tractor only.
VN1	Next-period value function for owning the large tractor and conventional planter.
V1	Current-period value function for owning the large tractor and conventional planter.
VN2	Next-period value function for owning the large tractor and no-till planter.
V2	Current-period value function for owning the large tractor and no-till planter.
VN4	Next-period value function for owning the small tractor and no-till planter.
V4	Current-period value function for owning the small tractor and no-till planter.
NKP	Next year's planter age (in years).
NKT	Next year's tractor age (in years).
NJ	Next year's experience level.
NOWN	Next year's ownership state.
POLICY	Desciption of the optimal policy in words.

The remaining variables are control variables or printed results for control variables found in the subroutines. See Tables 4.1-4.6 for descriptions. The numbers assigned to the policy variables if each control variable is the optimal choice correspond to the numbers in Tables 4.1-4.6 that describe the control variables. The only exceptions are the rental options on limited acreage and the HOLD option in subroutine DEC01 when these additional rental options are considered. In this case the additional rental options correspond to policies 14-19 and the HOLD option corresponds to policy 20.

The Program for the Deterministic Model

```
C      DP Replacement With Leasing Problem, including 2 planters,
C         2 tractors, and experience with the 2nd planter.
C      Includes the option of keeping planter 1 while renting planter 2.
C      Subroutines include conditional print statements to limit output.
C      ****************************************************************
$STORAGE:2
       PROGRAM RPLS2XR
       CHARACTER*78 TITLE
       CHARACTER*32 POLICY
       INTEGER*1 P1(20,36,5,36), P2(20,36,5,36)
       INTEGER*1 P4(20,36,5,36)
       INTEGER*1 PL3(36,5,36), PL4(36,5,36), OWN, OB, OT
       INTEGER*1 N, MP, MT, IAGE1, IAGE2, IAGE3, IAGE4, KX, OWNP, OWNT
       REAL PR1, PR2, PR3, PR4, RNT1, RNT2, CN1, CN2, CN3, CN4
       REAL VL3(36,6), VL4(36,6)
       COMMON /VALS/ A, R1, R2, CN1, CN2, CN3, CN4, CX(5), OB, OT, MPOL
       COMMON /VALS/ PR1, PR2, PR3, PR4, RNT1, RNT2, C3(40)
       COMMON /VALS/ VN1(20,36,6), VN2(20,36,6)
       COMMON /VALS/ VN4(20,36,6), VLN3(36,6), VLN4(36,6)
       COMMON /OWN1/ C1(20), T1(20), S1(20), V1(20,36,6)
       COMMON /OWN2/ C2(20), T2(20), S2(20)
       COMMON /OWN3/ T3(40), S3(40), RK1, RK2, RK3
       COMMON /OWN4/ C4(40), T4(40), S4(40)
       COMMON /OWN23/ V2(20,36,6)
       COMMON /OWN24/ V4(20,36,6)

       OPEN (UNIT = 2, FILE = 'RPLS2XR.DAT')
       OPEN (UNIT = 4, FILE = 'D:\RPLS2X.OUT')
       READ(2,20) TITLE
   20  FORMAT(78A)
       WRITE(4,22) TITLE
   22  FORMAT(78A/)
       READ(2,25) N, MP, MT, IAGE1, IAGE2, IAGE3, IAGE4
       WRITE(4,25) N, MP, MT, IAGE1, IAGE2, IAGE3, IAGE4
   25  FORMAT(7I9)
       READ(2,30) CX(1), CX(2), CX(3), CX(4), DF, KX
       WRITE(4,30) CX(1), CX(2), CX(3), CX(4), DF, KX
   30  FORMAT(5F9.4,I9)
       READ(2,32) PR1, RNT1, PR2, RNT2, PR3, PR4
       WRITE(4,32) PR1, RNT1, PR2, RNT2, PR3, PR4
   32  FORMAT(6F9.4)
       READ(2,35) RK1, RK2, RK3
       WRITE(4,35) RK1, RK2, RK3
   35  FORMAT(3F9.4)
       KPI = IAGE1
       IF (IAGE2 .GT. IAGE1) KPI = IAGE2
       KTI = IAGE3
       IF (IAGE4 .GT. IAGE3) KTI = IAGE4
       NP1 = N+1
       MPP1 = MP+1
       MTP2 = MT+2
       MPOL = 36
       A = 1.0 / (1.0 + DF)
       OWNT = 0
       IF (IAGE3 .GT. 0) THEN
```

```
            OWNT = 1
            IF (IAGE1 .GT. 0) THEN
                OWN = 13
            ELSE IF (IAGE2 .GT. 0) THEN
                OWN = 23
            ELSE
                OWN = 3
            END IF
        ELSE IF (IAGE4 .GT. 0) THEN
            OWNT = 2
            IF (IAGE2 .GT. 0) THEN
                OWN = 24
            ELSE
                OWN = 4
            END IF
        END IF
        OWNP = 0
        IF (IAGE1 .GT. 0) THEN
            OWNP = 1
        ELSE IF (IAGE2 .GT. 0) THEN
            OWNP = 2
        END IF

        READ(2,40) R1, R2, OB, OT
        WRITE(4,40) R1, R2, OB, OT
   40   FORMAT(2F9.4,2I9)
        READ(2,50) CN1, CN2, CN3, CN4
        WRITE(4,50) CN1, CN2, CN3, CN4
        DO 45 K=1,19
        READ(2,50) C1(K), C2(K), T1(K), T2(K)
        S1(K) = T1(K)
        S2(K) = T2(K)
   45   WRITE(4,50) C1(K), C2(K), T1(K), T2(K)
   50   FORMAT(4F9.4)
        DO 60 K=1,40
        READ(2,65) C3(K), C4(K), T3(K), T4(K)
        S3(K) = T3(K)
        S4(K) = T4(K)
   60   WRITE(4,65) C3(K), C4(K), T3(K), T4(K)
   65   FORMAT(4F9.4)
        CLOSE (2)
        DO 15 K=MPP1,20
        C1(K) = 9999.
        C2(K) = 9999.
        S1(K) = 0.
        S2(K) = 0.
        T1(K) = 0.
   15   T2(K) = 0.
        DO 16 K=MTP2,40
        C3(K) = 9999.
        C4(K) = 9999.
        S3(K) = 0.
        S4(K) = 0.
        T3(K) = 0.
   16   T4(K) = 0.
C       ***********************************************************************
C       SET TERMINAL PERIOD VALUE FUNCTIONS
```

```
C     ********************************************************************
      DO 3 J=1,5
           DO 3 KT=1,MTP2
                DO 2 KP=1,MPP1
                    VN1(KP,KT,J) = -S1(KP) - S3(KT)
                    VN2(KP,KT,J) = -S2(KP) - S3(KT)
    2               VN4(KP,KT,J) = -S2(KP) - S4(KT)
                    VLN3(KT,J) = -S3(KT)
                    VLN4(KT,J) = -S4(KT)
    3 CONTINUE
C     ********************************************************************
C     BACKWARDS RECURSIVE CALCULATION OF THE VALUE FUNCTION AND POLICIES
C     ********************************************************************
      DO 8 II = 1,N
           I = N - II + 1
           IM1 = N - II
           JM1 = IM1 * 2
           IF (IM1 .GT. MPP1) IM1 = MPP1
           IF (JM1 .GT. MTP2) JM1 = MTP2
           IHI = IM1 + KPI
           JHI = JM1 + KTI
           IF (IHI .GT. 20) IHI = 20
           IF (JHI .GT. 36) JHI = 36
           WRITE(4,80) I
   80      FORMAT('YEAR ',I2)
           DO 6 J=1,4
               DO 6 KT=1,JHI
                      CALL DECL3(KT, J, I, PL3, VL3)
                      CALL DECL4(KT, J, I, PL4, VL4)
                      DO 6 KP = 1,IHI
                            CALL DECO1(KP, KT, J, I, P1)
                            CALL DECO2(KP, KT, J, I, P2)
                            CALL DECO4(KP, KT, J, I, P4)
    6      CONTINUE
C     RESET THE NEXT PERIOD VALUE FUNCTIONS
      DO 36 KT=1,JHI
            DO 38 J=1,4
                    VLN3(KT,J) = VL3(KT,J)
   38               VLN4(KT,J) = VL4(KT,J)
                    VLN3(KT,5) = VL3(KT,4)
                    VLN4(KT,5) = VL4(KT,4)
                    DO 36 KP=1,IHI
                         DO 39 J=1,4
                              VN1(KP,KT,J) = V1(KP,KT,J)
                              VN2(KP,KT,J) = V2(KP,KT,J)
   39                         VN4(KP,KT,J) = V4(KP,KT,J)
                              VN1(KP,KT,5) = V1(KP,KT,4)
                              VN2(KP,KT,5) = V2(KP,KT,4)
                              VN4(KP,KT,5) = V4(KP,KT,4)
   36           CONTINUE
    8 CONTINUE
C     ********************************************************************
C     RECONSTRUCT THE OPTIMAL POLICIES
C     ********************************************************************
      KP = KPI
      KT = KTI
      J = KX
```

```
      NJ = KX
      IF (OWNT .EQ. 1) THEN
          WRITE(4,90) KP, OWNP
      ELSE IF (OWNT .EQ. 2) THEN
          WRITE(4,92) KP, OWNP
      END IF
90    FORMAT('OPT. POLICY STARTING WITH A',I2,' YR. OLD PLANTER OF TYPE'
     +,I2,' AND LARGE TRACTOR IS:',/)
92    FORMAT('OPT. POLICY STARTING WITH A',I2,' YR. OLD PLANTER OF TYPE'
     +,I2,' AND SMALL TRACTOR IS:',/)

      DO 10 I=1,36

          WRITE(4,94) I, KP, KT, J
94        FORMAT(4X,'YEAR: ',I2,'  PLANTER AGE:',I2,'  TRACTOR AGE:',
     +I2,'  J:',I2)

          IF (OWN .EQ. 13) THEN

              IF (P1(KP, KT, J, I) .EQ. 1) THEN
                      POLICY = 'REPLACE PLANTER 1'
                      NKP = 1
                      NKT = KT + 2
                      NOWN = 13
              ELSE IF (P1(KP, KT, J, I) .EQ. 2) THEN
                      POLICY = 'REPLACE W/ PLANTER 2'
                      NKP = 1
                      NKT = KT + 1
                      NJ = J + 1
                      NOWN = 23
              ELSE IF (P1(KP, KT, J, I) .EQ. 3) THEN
                      POLICY = 'REPLACE LARGE TRACTOR'
                      NKP = KP + 1
                      NKT = 2
                      NOWN = 13
              ELSE IF (P1(KP, KT, J, I) .EQ. 4) THEN
                      POLICY = 'REPLACE BOTH MACHINES'
                      NKP = 1
                      NKT = 2
                      NOWN = 13
              ELSE IF (P1(KP, KT, J, I) .EQ. 5) THEN
                      POLICY = 'REPLACE W/ LARGE TCTR, PLTR 2.'
                      NKP = 1
                      NKT = 1
                      NJ = J + 1
                      NOWN = 23
              ELSE IF (P1(KP, KT, J, I) .EQ. 6) THEN
                      POLICY = 'REPLACE W/ SMALL TCTR, PLTR 2.'
                      NKP = 1
                      NKT = 1
                      NJ = J + 1
                      NOWN = 24
              ELSE IF (P1(KP, KT, J, I) .EQ. 7) THEN
                      POLICY = 'RENT PLANTER 1'
                      NKP = 0
                      NKT = KT + 2
                      NOWN = 3
```

```
ELSE IF (P1(KP, KT, J, I) .EQ. 8) THEN
        POLICY = 'RENT PLANTER 2'
        NKP = 0
        NKT = KT + 1
        NJ = J + 1
        NOWN = 3
ELSE IF (P1(KP, KT, J, I) .EQ. 9) THEN
        POLICY = 'REPLACE L. TCTR., RENT PLTR. 1'
        NKP = 0
        NKT = 2
        NOWN = 3
ELSE IF (P1(KP, KT, J, I) .EQ. 10) THEN
        POLICY = 'REPLACE L. TCTR., RENT PLTR. 2'
        NKP = 0
        NKT = 1
        NJ = J + 1
        NOWN = 3
ELSE IF (P1(KP, KT, J, I) .EQ. 11) THEN
        POLICY = 'RPLCE W/SMALL TCTR. RENT PLTR 2'
        NKP = 0
        NKT = 1
        NJ = J + 1
        NOWN = 4
ELSE IF (P1(KP, KT, J, I) .EQ. 12) THEN
        POLICY = 'RENT PLANTER 2, KEEP PLANTER 1'
        NKP = KP + 1
        NKT = KT + 2
        NJ = J + 1
        NOWN = 13
ELSE IF (P1(KP, KT, J, I) .EQ. 13) THEN
        POLICY = 'RPLCE TCTR, RNT PLTR 2, KEEP 1'
        NKP = KP + 1
        NKT = 1
        NJ = J + 1
        NOWN = 13
ELSE IF (P1(KP, KT, J, I) .EQ. 14) THEN
        POLICY = 'RNT PL 2 ON 60 A, KEEP P1'
        NKP = KP + 1
        NKT = KT + 2
        NJ = J + 1
        NOWN = 13
ELSE IF (P1(KP, KT, J, I) .EQ. 15) THEN
        POLICY = 'RNT PL 2 ON 120 A, KEEP P1'
        NKP = KP + 1
        NKT = KT + 2
        NJ = J + 1
        NOWN = 13
ELSE IF (P1(KP, KT, J, I) .EQ. 16) THEN
        POLICY = 'RNT PL 2 ON 240 A, KEEP P1'
        NKP = KP + 1
        NKT = KT + 2
        NJ = J + 1
        NOWN = 13
ELSE IF (P1(KP, KT, J, I) .EQ. 17) THEN
        POLICY = 'REPLACE T3, RENT PL 2 ON 60 A'
        NKP = KP + 1
        NKT = 1
```

```
            NJ = J + 1
            NOWN = 13
      ELSE IF (P1(KP, KT, J, I) .EQ. 18) THEN
            POLICY = 'REPLACE T3, RENT PL 2 ON 120 A'
            NKP = KP + 1
            NKT = 1
            NJ = J + 1
            NOWN = 13
      ELSE IF (P1(KP, KT, J, I) .EQ. 19) THEN
            POLICY = 'REPLACE T3, RENT PL 2 ON 240 A'
            NKP = KP + 1
            NKT = 1
            NJ = J + 1
            NOWN = 13
      ELSE IF (P1(KP, KT, J, I) .EQ. 20) THEN
            POLICY = 'KEEP BOTH MACHINES'
            NKP = KP + 1
            NKT = KT + 2
            NOWN = 13
      END IF
      WRITE(4,95) I, OWN, P1(KP, KT, J, I), POLICY

 ELSE IF (OWN .EQ. 23) THEN

      IF (P2(KP, KT, J ,I) .EQ. 1) THEN
            POLICY = 'REPLACE W/ PLANTER 1'
            NKP = 1
            NKT = KT + 2
            NOWN = 13
      ELSE IF (P2(KP, KT, J, I) .EQ. 2) THEN
            POLICY = 'REPLACE PLANTER 2'
            NKP = 1
            NKT = KT + 1
            NJ = J + 1
            NOWN = 23
      ELSE IF (P2(KP, KT, J, I) .EQ. 3) THEN
            POLICY = 'REPLACE LARGE TRACTOR.'
            NKP = KP + 1
            NKT = 1
            NJ = J + 1
            NOWN = 23
      ELSE IF (P2(KP, KT, J, I) .EQ. 4) THEN
            POLICY = 'REPLACE LRGE TCTR W/ SMALL TCTR'
            NKP = KP + 1
            NKT = 1
            NJ = J + 1
            NOWN = 24
      ELSE IF (P2(KP, KT, J, I) .EQ. 5) THEN
            POLICY = 'REPLACE W/ LARGE TCTR, PLTR. 1'
            NKP = 1
            NKT = 2
            NOWN = 13
      ELSE IF (P2(KP, KT, J, I) .EQ. 6) THEN
            POLICY = 'REPLACE W/ LARGE TCTR, PLTR 2.'
            NKP = 1
            NKT = 1
            NJ = J + 1
```

```
                NOWN = 23
          ELSE IF (P2(KP, KT, J, I) .EQ. 7) THEN
                POLICY = 'REPLACE W/ SMALL TCTR, PLTR 2.'
                NKP = 1
                NKT = 1
                NJ = J + 1
                NOWN = 24
          ELSE IF (P2(KP, KT, J, I) .EQ. 8) THEN
                POLICY = 'RENT PLANTER 1'
                NKP = 0
                NKT = KT + 2
                NOWN = 3
          ELSE IF (P2(KP, KT, J, I) .EQ. 9) THEN
                POLICY = 'RENT PLANTER 2'
                NKP = 0
                NKT = KT + 1
                NJ = J + 1
                NOWN = 3
          ELSE IF (P2(KP, KT, J, I) .EQ. 10) THEN
                POLICY = 'REPLACE L. TCTR., RENT PLTR. 1'
                NKP = 0
                NKT = 2
                NOWN = 3
          ELSE IF (P2(KP, KT, J, I) .EQ. 11) THEN
                POLICY = 'REPLACE L. TCTR., RENT PLTR. 2'
                NKP = 0
                NKT = 1
                NJ = J + 1
                NOWN = 3
          ELSE IF (P2(KP, KT, J, I) .EQ. 12) THEN
                POLICY = 'RPLCE W/SMALL TCTR. RENT PLTR 2'
                NKP = 0
                NKT = 1
                NJ = J + 1
                NOWN = 4
          ELSE IF (P2(KP, KT, J, I) .EQ. 13) THEN
                POLICY = 'KEEP BOTH MACHINES'
                NKP = KP + 1
                NKT = KT + 1
                NJ = J + 1
                NOWN = 23
          END IF
          WRITE(4,95) I, OWN, P2(KP, KT, J, I), POLICY

     ELSE IF (OWN .EQ. 24) THEN

          IF (P4(KP, KT, J, I) .EQ. 1) THEN
                POLICY = 'REPLACE PLANTER 2'
                NKP = 1
                NKT = KT + 1
                NJ = J + 1
                NOWN = 24
          ELSE IF (P4(KP, KT, J, I) .EQ. 2) THEN
                POLICY = 'REPLACE SMALL TCTR W/ LRGE TCTR'
                NKP = KP + 1
                NKT = 1
                NJ = J + 1
```

```
                NOWN = 23
        ELSE IF (P4(KP, KT, J, I) .EQ. 3) THEN
                POLICY = 'REPLACE SMALL TRACTOR.'
                NKP = KP + 1
                NKT = 1
                NJ = J + 1
                NOWN = 24
        ELSE IF (P4(KP, KT, J, I) .EQ. 4) THEN
                POLICY = 'REPLACE W/ LARGE TCTR, PLTR. 1'
                NKP = 1
                NKT = 2
                NOWN = 13
        ELSE IF (P4(KP, KT, J, I) .EQ. 5) THEN
                POLICY = 'REPLACE W/ LARGE TCTR, PLTR 2.'
                NKP = 1
                NKT = 1
                NJ = J + 1
                NOWN = 23
        ELSE IF (P4(KP, KT, J, I) .EQ. 6) THEN
                POLICY = 'REPLACE W/ SMALL TCTR, PLTR 2.'
                NKP = 1
                NKT = 1
                NJ = J + 1
                NOWN = 24
        ELSE IF (P4(KP, KT, J, I) .EQ. 7) THEN
                POLICY = 'RENT PLANTER 2'
                NKP = 0
                NKT = KT + 1
                NJ = J + 1
                NOWN = 4
        ELSE IF (P4(KP, KT, J, I) .EQ. 8) THEN
                POLICY = 'REPLACE L. TCTR., RENT PLTR. 1'
                NKP = 0
                NKT = 2
                NOWN = 3
        ELSE IF (P4(KP, KT, J, I) .EQ. 9) THEN
                POLICY = 'REPLACE L. TCTR., RENT PLTR. 2'
                NKP = 0
                NKT = 1
                NJ = J + 1
                NOWN = 3
        ELSE IF (P4(KP, KT, J, I) .EQ. 10) THEN
                POLICY = 'RPLCE W/SMALL TCTR. RENT PLTR 2'
                NKP = 0
                NKT = 1
                NJ = J + 1
                NOWN = 4
        ELSE IF (P4(KP, KT, J, I) .EQ. 11) THEN
                POLICY = 'KEEP BOTH MACHINES'
                NKP = KP + 1
                NKT = KT + 1
                NJ = J + 1
                NOWN = 24
        END IF
        WRITE(4,95) I, OWN, P4(KP, KT, J, I), POLICY

   ELSE IF (OWN .EQ. 3) THEN
```

```
     IF (PL3(KT, J, I) .EQ. 1) THEN
             POLICY = 'BUY PLANTER 1'
             NKP = 1
             NKT = KT + 2
             NOWN = 13
     ELSE IF (PL3(KT, J, I) .EQ. 2) THEN
             POLICY = 'BUY PLANTER 2'
             NKP = 1
             NKT = KT + 1
             NJ = J + 1
             NOWN = 23
     ELSE IF (PL3(KT, J, I) .EQ. 3) THEN
             POLICY = 'KEEP RENTING PLANTER 1'
             NKP = 0
             NKT = KT + 2
             NOWN = 3
     ELSE IF (PL3(KT, J, I) .EQ. 4) THEN
             POLICY = 'RENT PLANTER 2'
             NKP = 0
             NKT = KT + 1
             NJ = J + 1
             NOWN = 3
     ELSE IF (PL3(KT, J, I) .EQ. 5) THEN
             POLICY = 'BUY PLNTR 1, REPLACE TRACTOR'
             NKP = 1
             NKT = 2
             NOWN = 13
     ELSE IF (PL3(KT, J, I) .EQ. 6) THEN
             POLICY = 'BUY PLNTR 2, REPLACE TRACTOR'
             NKP = 1
             NKT = 1
             NJ = J + 1
             NOWN = 23
     ELSE IF (PL3(KT, J, I) .EQ. 7) THEN
             POLICY = 'BUY PLNTR 2 & SMALL TRACTOR'
             NKP = 1
             NKT = 1
             NJ = J + 1
             NOWN = 24
     ELSE IF (PL3(KT, J, I) .EQ. 8) THEN
             POLICY = 'REPLACE TRACTOR, RENT PLANTER 1'
             NKP = 0
             NKT = 2
             NOWN = 3
     ELSE IF (PL3(KT, J, I) .EQ. 9) THEN
             POLICY = 'REPLACE TRACTOR, RENT PLANTER 2'
             NKP = 0
             NKT = 1
             NJ = J + 1
             NOWN = 3
     END IF
     WRITE(4,95) I, OWN, PL3(KT, J, I), POLICY

ELSE IF (OWN .EQ. 4) THEN

     IF (PL4(KT, J, I) .EQ. 1) THEN
             POLICY = 'BUY PLANTER 2'
```

```
                NKP = 1
                NKT = KT + 1
                NJ = J + 1
                NOWN = 24
        ELSE IF (PL4(KT, J, I) .EQ. 2) THEN
                POLICY = 'KEEP RENTING PLANTER 2'
                NKP = 0
                NKT = KT + 1
                NJ = J + 1
                NOWN = 4
        ELSE IF (PL4(KT, J, I) .EQ. 3) THEN
                POLICY = 'BUY LARGE TRACTOR & PLANTER 1'
                NKP = 1
                NKT = 2
                NOWN = 13
        ELSE IF (PL4(KT, J, I) .EQ. 4) THEN
                POLICY = 'BUY LARGE TRACTOR & PLANTER 2'
                NKP = 1
                NKT = 1
                NJ = J + 1
                NOWN = 23
        ELSE IF (PL4(KT, J, I) .EQ. 5) THEN
                POLICY = 'BUY SMALL TRACTOR & PLANTER 2'
                NKP = 1
                NKT = 1
                NJ = J + 1
                NOWN = 24
        ELSE IF (PL4(KT, J, I) .EQ. 6) THEN
                POLICY = 'RPLCE SMALL TCTR, RENT PLNTR 2'
                NKP = 0
                NKT = 1
                NJ = J + 1
                NOWN = 4
        END IF
        WRITE(4,95) I, OWN, PL4(KT, J, I), POLICY

     END IF

     IF (NJ .GT. J) J = NJ
     IF(J .GT. 4) J = 4
     KP = NKP
     KT = NKT
     OWN = NOWN

 95  FORMAT('IN YEAR ',I2,' OWNING: ',I2,'  POLICY: ',I2,3X,A32)

 10 CONTINUE

    CLOSE (4)
2000 END

    SUBROUTINE DECL3 (KT, J, I, PL3, VL3)
    INTEGER*1 PL3(36,5,36), OB, OT
    REAL VL3(36,6)
    COMMON /VALS/ A, R1, R2, CN1, CN2, CN3, CN4, CX(5), OB, OT, MPOL
    COMMON /VALS/ PR1, PR2, PR3, PR4, RNT1, RNT2, C3(40)
    COMMON /VALS/ VN1(20,36,6), VN2(20,36,6)
```

```
      COMMON /VALS/ VN4(20,36,6), VLN3(36,6), VLN4(36,6)
      COMMON /OWN3/ T3(40), S3(40), RK1, RK2, RK3

      BUY1 = PR1 - R1 + CN1 + C3(KT)+C3(KT+1) + A*VN1(1,KT+2,J)
      BUY2 = PR2 - R2 + (CN2+C3(KT))*CX(J) + A*VN2(1,KT+1,J+1)
      CRNT1 = RNT1 - R1 + CN1 + C3(KT)+C3(KT+1) + A*VLN3(KT+2,J)
      CRNT2 = RNT2 - R2 + (CN2+C3(KT))*CX(J) + A*VLN3(KT+1,J+1)
      BUY13 = PR1 + PR3 - T3(KT) - R1 + CN1+CN3+C3(1) + A*VN1(1,2,J)
      BUY23 = PR2 + PR3 - T3(KT) - R2 + (CN2+CN3)*CX(J)+A*VN2(1,1,J+1)
      BUY24 = PR2 + PR4 - T3(KT) - R2 + (CN2+CN4)*CX(J)+A*VN4(1,1,J+1)
      CRNT31 = PR3-T3(KT) + RNT1 - R1 + CN1+CN3+C3(1) + A*VLN3(2,J)
      CRNT32 = PR3-T3(KT) + RNT2 - R2 + (CN2+CN3)*CX(J) + A*VLN3(1,J+1)

      CB = AMIN1(BUY1,BUY2,BUY13,BUY23,BUY24)
      CR = AMIN1(CRNT1,CRNT2,CRNT31,CRNT32)
      VL3(KT,J) = AMIN1(CB,CR)

      IF (I .LE. MPOL) THEN
          IF (VL3(KT,J) .EQ. BUY1) PL3(KT,J,I) = 1
          IF (VL3(KT,J) .EQ. BUY2) PL3(KT,J,I) = 2
          IF (VL3(KT,J) .EQ. BUY13) PL3(KT,J,I) = 3
          IF (VL3(KT,J) .EQ. BUY23) PL3(KT,J,I) = 4
          IF (VL3(KT,J) .EQ. BUY24) PL3(KT,J,I) = 5
          IF (VL3(KT,J) .EQ. CRNT1) PL3(KT,J,I) = 6
          IF (VL3(KT,J) .EQ. CRNT2) PL3(KT,J,I) = 7
          IF (VL3(KT,J) .EQ. CRNT31) PL3(KT,J,I) = 8
          IF (VL3(KT,J) .EQ. CRNT32) PL3(KT,J,I) = 9
      END IF

      IF (I .GE. OB .AND. I .LE. OT .AND. J .EQ. 9) THEN
      WRITE(4,101) BUY1, BUY2, BUY13, BUY23, BUY24
  101 FORMAT('RENTL:',5F9.1)
      WRITE(4,102) CRNT1, CRNT2, CRNT31, CRNT32, KT, J, I, PL3(KT,J,I)
  102 FORMAT('RENTL:',4F9.1,12X,'PL3(',I2,',',I1,',',I2,') = ',I2)
      END IF
      END

      SUBROUTINE DECL4 (KT, J, I, PL4, VL4)
      INTEGER*1 PL4(36,5,36), OB, OT
      REAL VL4(36,6)
      COMMON /VALS/ A, R1, R2, CN1, CN2, CN3, CN4, CX(5), OB, OT, MPOL
      COMMON /VALS/ PR1, PR2, PR3, PR4, RNT1, RNT2, C3(40)
      COMMON /VALS/ VN1(20,36,6), VN2(20,36,6)
      COMMON /VALS/ VN4(20,36,6), VLN3(36,6), VLN4(36,6)
      COMMON /OWN4/ C4(40), T4(40), S4(40)

      BUY2 = PR2 - R2 + (CN2+C4(KT))*CX(J) + A*VN4(1,KT+1,J+1)
      CRNT2 = RNT2 - R2 + (CN2+C4(KT))*CX(J) + A*VLN4(KT+1,J+1)
      BUY13 = PR1 + PR3 - T4(KT) - R1 + CN1+CN3+C3(1) + A*VN1(1,2,J)
      BUY23 = PR2 + PR3 - T4(KT) - R2 + (CN2+CN3)*CX(J) +A*VN2(1,1,J+1)
      BUY24 = PR2 + PR4 - T4(KT) - R2 + (CN2+CN4)*CX(J) +A*VN4(1,1,J+1)
      CRNT42 = PR4-T4(KT) + RNT2 - R2 + (CN2+CN4)*CX(J) + A*VLN4(1,J+1)

      CB = AMIN1(BUY2,BUY13,BUY23,BUY24)
      CR = AMIN1(CRNT2,CRNT42)
      VL4(KT,J) = AMIN1(CB,CR)
```

```
      IF (I .LE. MPOL) THEN
          IF (VL4(KT,J) .EQ. BUY2) PL4(KT,J,I) = 1
          IF (VL4(KT,J) .EQ. BUY13) PL4(KT,J,I) = 2
          IF (VL4(KT,J) .EQ. BUY23) PL4(KT,J,I) = 3
          IF (VL4(KT,J) .EQ. BUY24) PL4(KT,J,I) = 4
          IF (VL4(KT,J) .EQ. CRNT2) PL4(KT,J,I) = 5
          IF (VL4(KT,J) .EQ. CRNT42) PL4(KT,J,I) = 6
      END IF

      IF (I .GE. OB .AND. I .LE. OT .AND. J .EQ. 9) THEN
      WRITE(4,201) BUY2, BUY13, BUY23, BUY24
  201 FORMAT('RENTS:',4F9.1)
      WRITE(4,202) CRNT2, CRNT42, KT, J, I, PL4(KT,J,I)
  202 FORMAT('RENTS:',2F9.1,30X,'PL4(',I2,',',I1,',',I2,') = ',I2)
      END IF
      END

      SUBROUTINE DEC01 (KP, KT, J, I, P1)
      INTEGER*1 P1(20,36,5,36), OB, OT
      COMMON /VALS/ A, R1, R2, CN1, CN2, CN3, CN4, CX(5), OB, OT, MPOL
      COMMON /VALS/ PR1, PR2, PR3, PR4, RNT1, RNT2, C3(40)
      COMMON /VALS/ VN1(20,36,6), VN2(20,36,6)
      COMMON /VALS/ VN4(20,36,6), VLN3(36,6), VLN4(36,6)
      COMMON /OWN1/ C1(20), T1(20), S1(20), V1(20,36,6)
      COMMON /OWN3/ T3(40), S3(40), RK1, RK2, RK3

      REPL1 = PR1 - T1(KP) - R1 + CN1+C3(KT)+C3(KT+1) + A*VN1(1,KT+2,J)
      REPL2 = PR2 - T1(KP) - R2 + (CN2+C3(KT))*CX(J) +A*VN2(1,KT+1,J+1)
      REPL3 = PR3 - T3(KT) - R1 + C1(KP)+CN3+C3(1) + A*VN1(KP+1,2,J)
      REPL13 = PR1+PR3-T1(KP)-T3(KT) - R1 + CN1+CN3+C3(1) +A*VN1(1,2,J)
      REPL23 = PR2+PR3-T1(KP)-T3(KT) - R2 + (CN2+CN3)*CX(J) + A*VN2(1,1,
     +J+1)
      REPL24 = PR2+PR4-T1(KP)-T3(KT) - R2 + (CN2+CN4)*CX(J) + A*VN4(1,1,
     +J+1)
      RENT1 = -S1(KP) + RNT1 - R1 + CN1+C3(KT)+C3(KT+1) + A*VLN3(KT+2,J)
      RENT2 = -S1(KP)+RNT2 - R2 + (CN2+C3(KT))*CX(J) + A*VLN3(KT+1,J+1)
      RNT13 = -S1(KP)+RNT1+PR3-T3(KT) - R1 + CN1+CN3+C3(1) + A*VLN3(2,J)
      RNT23 = -S1(KP)+RNT2+PR3-T3(KT) - R2 + (CN2+CN3)*CX(J) + A*VLN3(1,
     +J+1)
      RNT24 = -S1(KP)+RNT2+PR4-T3(KT) - R2 + (CN2+CN4)*CX(J) + A*VLN4(1,
     +J+1)
      RNT2K = RNT2 - R2 + (CN2+C3(KT))*CX(J) + A*VN1(KP,KT+1,J+1)
      RT23K = RNT2+PR3-T3(KT) - R2 + (CN2+CN3)*CX(J) + A*VN1(KP,1,J+1)
      RT2K2 = RK1-R1*0.9-R2*0.1+C1(KP)*0.9+C3(KT)+C3(KT+1)+CN2*CX(J)*0.1
     +        + (1+(CX(J)-1.0)*0.2)*C3(KT+1) + A*VN1(KP+1,KT+2,J+1)
      RT2K3 = RK2-R1*0.8-R2*0.2+C1(KP)*0.8+C3(KT)+C3(KT+1)+CN2*CX(J)*0.2
     +        + (1+(CX(J)-1.0)*0.4)*C3(KT+1) + A*VN1(KP+1,KT+2,J+1)
      RT2K4 = RK3-R1*0.6-R2*0.4+C1(KP)*0.6+C3(KT)+C3(KT+1)+CN2*CX(J)*0.4
     +        + (1+(CX(J)-1.0)*0.8)*C3(KT+1) + A*VN1(KP+1,KT+2,J+1)
      R23K2 = PR3-T3(KT)+RK1-R1*0.9-R2*0.1+C1(KP)*0.9+C3(KT)+C3(KT+1)+
     +    CN2*CX(J)*0.1+(1+(CX(J)-1.0)*0.2)*C3(KT+1) + A*VN1(KP+1,2,J+1)
      R23K3 = PR3-T3(KT)+RK2-R1*0.8-R2*0.2+C1(KP)*0.8+C3(KT)+C3(KT+1)+
     +    CN2*CX(J)*0.2+(1+(CX(J)-1.0)*0.4)*C3(KT+1) + A*VN1(KP+1,2,J+1)
      R23K4 = PR3-T3(KT)+RK3-R1*0.6-R2*0.4+C1(KP)*0.6+C3(KT)+C3(KT+1)+
     +    CN2*CX(J)*0.4+(1+(CX(J)-1.0)*0.8)*C3(KT+1) + A*VN1(KP+1,2,J+1)
      HOLD = -R1 + C1(KP) + C3(KT)+C3(KT+1) + A*VN1(KP+1,KT+2,J)
```

```
      CB = AMIN1(REPL1,REPL2,REPL3,REPL13,REPL23,REPL24,HOLD)
      CR = AMIN1(RENT1,RENT2,RNT13,RNT23,RNT24)
      CRK = AMIN1(RNT2K,RT23K,RT2K2,RT2K3,RT2K4,R23K2,R23K3,R23K4)
      V1(KP,KT,J) = AMIN1(CB,CR,CRK)

      DRPL1 = REPL1 - V1(KP,KT,J)
      DRPL2 = REPL2 - V1(KP,KT,J)
      DRPL3 = REPL3 - V1(KP,KT,J)
      DRPL13 = REPL13 - V1(KP,KT,J)
      DRPL23 = REPL23 - V1(KP,KT,J)
      DRPL24 = REPL24 - V1(KP,KT,J)
      DRNT1 = RENT1 - V1(KP,KT,J)
      DRNT2 = RENT2 - V1(KP,KT,J)
      DRNT13 = RNT13 - V1(KP,KT,J)
      DRNT23 = RNT23 - V1(KP,KT,J)
      DRNT24 = RNT24 - V1(KP,KT,J)
      DRNT2K = RNT2K - V1(KP,KT,J)
      DRT23K = RT23K - V1(KP,KT,J)
      DRT2K2 = RT2K2 - V1(KP,KT,J)
      DRT2K3 = RT2K3 - V1(KP,KT,J)
      DRT2K4 = RT2K4 - V1(KP,KT,J)
      DR23K2 = R23K2 - V1(KP,KT,J)
      DR23K3 = R23K3 - V1(KP,KT,J)
      DR23K4 = R23K4 - V1(KP,KT,J)
      DHOLD = HOLD - V1(KP,KT,J)

      IF (I .LE. MPOL) THEN
          IF (V1(KP,KT,J) .EQ. REPL1)  P1(KP,KT,J,I) =  1
          IF (V1(KP,KT,J) .EQ. REPL2)  P1(KP,KT,J,I) =  2
          IF (V1(KP,KT,J) .EQ. REPL3)  P1(KP,KT,J,I) =  3
          IF (V1(KP,KT,J) .EQ. REPL13) P1(KP,KT,J,I) =  4
          IF (V1(KP,KT,J) .EQ. REPL23) P1(KP,KT,J,I) =  5
          IF (V1(KP,KT,J) .EQ. REPL24) P1(KP,KT,J,I) =  6
          IF (V1(KP,KT,J) .EQ. RENT1)  P1(KP,KT,J,I) =  7
          IF (V1(KP,KT,J) .EQ. RENT2)  P1(KP,KT,J,I) =  8
          IF (V1(KP,KT,J) .EQ. RNT13)  P1(KP,KT,J,I) =  9
          IF (V1(KP,KT,J) .EQ. RNT23)  P1(KP,KT,J,I) = 10
          IF (V1(KP,KT,J) .EQ. RNT24)  P1(KP,KT,J,I) = 11
          IF (V1(KP,KT,J) .EQ. RNT2K)  P1(KP,KT,J,I) = 12
          IF (V1(KP,KT,J) .EQ. RT23K)  P1(KP,KT,J,I) = 13
          IF (V1(KP,KT,J) .EQ. RT2K2)  P1(KP,KT,J,I) = 14
          IF (V1(KP,KT,J) .EQ. RT2K3)  P1(KP,KT,J,I) = 15
          IF (V1(KP,KT,J) .EQ. RT2K4)  P1(KP,KT,J,I) = 16
          IF (V1(KP,KT,J) .EQ. R23K2)  P1(KP,KT,J,I) = 17
          IF (V1(KP,KT,J) .EQ. R23K3)  P1(KP,KT,J,I) = 18
          IF (V1(KP,KT,J) .EQ. R23K4)  P1(KP,KT,J,I) = 19
          IF (V1(KP,KT,J) .EQ. HOLD)   P1(KP,KT,J,I) = 20
      END IF

      IF (I .GE. OB .AND. I .LE. OT .AND. J .LE. 3) THEN
      WRITE(4,301) DRPL1, DRPL2, DRPL3, DRPL13, DRPL23, DRPL24, DRNT1,
     +DRNT2
      WRITE(4,301) DRNT13,DRNT23,DRNT24,DRNT2K,DRT23K,DRT2K2,DRT2K3,
     +DRT2K4
  301 FORMAT('OWN1L:',8F8.2)
      WRITE(4,302) DR23K2, DR23K3, DR23K4, DHOLD, KP, KT, J, I,
     +P1(KP, KT, J, I)
```

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302 FORMAT('OWN1L:',4F8.2,3X,'P1(',I2,',',I2,',',I1,',',I2,')=',I2)
      END IF
      END

      SUBROUTINE DECO2 (KP, KT, J, I, P2)
      INTEGER*1 P2(20,36,5,36), OB, OT
      COMMON /VALS/ A, R1, R2, CN1, CN2, CN3, CN4, CX(5), OB, OT, MPOL
      COMMON /VALS/ PR1, PR2, PR3, PR4, RNT1, RNT2, C3(40)
      COMMON /VALS/ VN1(20,36,6), VN2(20,36,6)
      COMMON /VALS/ VN4(20,36,6), VLN3(36,6), VLN4(36,6)
      COMMON /OWN2/ C2(20), T2(20), S2(20)
      COMMON /OWN3/ T3(40), S3(40), RK1, RK2, RK3
      COMMON /OWN23/ V2(20,36,6)

      REPL1 = PR1 - T2(KP) - R1 + CN1+C3(KT)+C3(KT+1) + A*VN1(1,KT+2,J)
      REPL2 = PR2 - T2(KP) - R2 + (CN2+C3(KT))*CX(J) +A*VN2(1,KT+1,J+1)
      REPL3 = PR3 - T3(KT) - R2 + (C2(KP)+CN3)*CX(J) +A*VN2(KP+1,1,J+1)
      REPL4 = PR4 - T3(KT) - R2 + (C2(KP)+CN4)*CX(J) + A*VN4(KP+1,1,J+1)
      REPL13 = PR1+PR3-T2(KP)-T3(KT) - R1 + CN1+CN3+C3(1) + A*VN1(1,2,J)
      REPL23 = PR2+PR3-T2(KP)-T3(KT) - R2 + (CN2+CN3)*CX(J) + A*VN2(1,1,
     +J+1)
      REPL24 = PR2+PR4-T2(KP)-T3(KT) - R2 + (CN2+CN4)*CX(J) + A*VN4(1,1,
     +J+1)
      RENT1 = -S2(KP) + RNT1 - R1 + CN1+C3(KT)+C3(KT+1) + A*VLN3(KT+2,J)
      RENT2 = -S2(KP)+RNT2 - R2 + (CN2+C3(KT))*CX(J) + A*VLN3(KT+1,J+1)
      RNT13 = -S2(KP)+RNT1+PR3-T3(KT) - R1 + CN1+CN3+C3(1) + A*VLN3(2,J)
      RNT23 = -S2(KP)+RNT2+PR3-T3(KT) - R2 + (CN2+CN3)*CX(J) + A*VLN3(1,
     +J+1)
      RNT24 = -S2(KP)+RNT2+PR4-T3(KT) - R2 + (CN2+CN4)*CX(J) + A*VLN4(1,
     +J+1)
      HOLD = -R2 + (C2(KP)+C3(KT))*CX(J) + A*VN2(KP+1,KT+1,J+1)

      CB = AMIN1(REPL1,REPL2,REPL3,REPL4,REPL13,REPL23,REPL24,HOLD)
      CR = AMIN1(RENT1,RENT2,RNT13,RNT23,RNT24)
      V2(KP,KT,J) = AMIN1(CB,CR)

      IF (I .LE. MPOL) THEN
          IF (V2(KP,KT,J) .EQ. REPL1)  P2(KP,KT,J,I) =  1
          IF (V2(KP,KT,J) .EQ. REPL2)  P2(KP,KT,J,I) =  2
          IF (V2(KP,KT,J) .EQ. REPL3)  P2(KP,KT,J,I) =  3
          IF (V2(KP,KT,J) .EQ. REPL4)  P2(KP,KT,J,I) =  4
          IF (V2(KP,KT,J) .EQ. REPL13) P2(KP,KT,J,I) =  5
          IF (V2(KP,KT,J) .EQ. REPL23) P2(KP,KT,J,I) =  6
          IF (V2(KP,KT,J) .EQ. REPL24) P2(KP,KT,J,I) =  7
          IF (V2(KP,KT,J) .EQ. RENT1)  P2(KP,KT,J,I) =  8
          IF (V2(KP,KT,J) .EQ. RENT2)  P2(KP,KT,J,I) =  9
          IF (V2(KP,KT,J) .EQ. RNT13)  P2(KP,KT,J,I) = 10
          IF (V2(KP,KT,J) .EQ. RNT23)  P2(KP,KT,J,I) = 11
          IF (V2(KP,KT,J) .EQ. RNT24)  P2(KP,KT,J,I) = 12
          IF (V2(KP,KT,J) .EQ. HOLD)   P2(KP,KT,J,I) = 13
      END IF

      IF (I .GE. OB .AND. I .LE. OT .AND. J .EQ. 9) THEN
      WRITE(4,401) REPL1, REPL2, REPL3, REPL4, REPL13, REPL23, REPL24,
     +RENT1
401 FORMAT('OWN2L:',8F9.1)
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    WRITE(4,402) RENT2, RNT13, RNT23, RNT24, HOLD, KP, KT, J, I, P2(KP
   +,KT,J,I)
402 FORMAT('OWN2L:',5F9.1,3X,'P2(',I2,',',I2,',',I1,',',I2,')=',I2)
    END IF
    END

    SUBROUTINE DECO4 (KP, KT, J, I, P4)
    INTEGER*1 P4(20,36,5,36), OB, OT
    COMMON /VALS/ A, R1, R2, CN1, CN2, CN3, CN4, CX(5), OB, OT, MPOL
    COMMON /VALS/ PR1, PR2, PR3, PR4, RNT1, RNT2, C3(40)
    COMMON /VALS/ VN1(20,36,6), VN2(20,36,6)
    COMMON /VALS/ VN4(20,36,6), VLN3(36,6), VLN4(36,6)
    COMMON /OWN2/ C2(20), T2(20), S2(20)
    COMMON /OWN4/ C4(40), T4(40), S4(40)
    COMMON /OWN24/ V4(20,36,6)

    REPL2 = PR2-T2(KP) - R2 + (CN2+C4(KT))*CX(J) + A*VN4(1,KT+1,J+1)
    REPL3 = PR3-T4(KT) - R2 + (C2(KP) + CN3)*CX(J) + A*VN2(KP+1,1,J+1)
    REPL4 = PR4-T4(KT) - R2 + (C2(KP) + CN4)*CX(J) + A*VN4(KP+1,1,J+1)
    REPL13 = PR1+PR3-T2(KP)-T4(KT) - R1 + CN1+CN3+C3(1) + A*VN1(1,2,J)
    REPL23 = PR2+PR3-T2(KP)-T4(KT) - R2 + (CN2+CN3)*CX(J) + A*VN2(1,1,
   +J+1)
    REPL24 = PR2+PR4-T2(KP)-T4(KT) - R2 + (CN2+CN4)*CX(J) + A*VN4(1,1,
   +J+1)
    RENT2 = -S2(KP)+RNT2 - R2 + (CN2+C4(KT))*CX(J) + A*VLN4(KT+1,J+1)
    RNT13 = -S2(KP)+RNT1+PR3-T4(KT) - R1 + CN1+CN3+C3(1) + A*VLN3(2,J)
    RNT23 = -S2(KP)+RNT2+PR3-T4(KT) - R2 + (CN2+CN3)*CX(J) + A*VLN3(1,
   +J+1)
    RNT24 = -S2(KP)+RNT2+PR4-T4(KT) - R2 + (CN2+CN4)*CX(J) + A*VLN4(1,
   +J+1)
    HOLD = -R2 + (C2(KP) + C4(KT))*CX(J) + A*VN4(KP+1,KT+1,J+1)

    CB = AMIN1(REPL2,REPL3,REPL4,REPL13,REPL23,REPL24,HOLD)
    CR = AMIN1(RENT2,RNT13,RNT23,RNT24)
    V4(KP,KT,J) = AMIN1(CB,CR)

    IF (I .LE. MPOL) THEN
        IF (V4(KP,KT,J) .EQ. REPL2)  P4(KP,KT,J,I) =  1
        IF (V4(KP,KT,J) .EQ. REPL3)  P4(KP,KT,J,I) =  2
        IF (V4(KP,KT,J) .EQ. REPL4)  P4(KP,KT,J,I) =  3
        IF (V4(KP,KT,J) .EQ. REPL13) P4(KP,KT,J,I) =  4
        IF (V4(KP,KT,J) .EQ. REPL23) P4(KP,KT,J,I) =  5
        IF (V4(KP,KT,J) .EQ. REPL24) P4(KP,KT,J,I) =  6
        IF (V4(KP,KT,J) .EQ. RENT2)  P4(KP,KT,J,I) =  7
        IF (V4(KP,KT,J) .EQ. RNT13)  P4(KP,KT,J,I) =  8
        IF (V4(KP,KT,J) .EQ. RNT23)  P4(KP,KT,J,I) =  9
        IF (V4(KP,KT,J) .EQ. RNT24)  P4(KP,KT,J,I) = 10
        IF (V4(KP,KT,J) .EQ. HOLD)   P4(KP,KT,J,I) = 11
    END IF

    IF (I .GE. OB .AND. I .LE. OT .AND. J .EQ. 9) THEN
    WRITE(4,501) REPL2, REPL3, REPL4, REPL13, REPL23, REPL24, RENT2
501 FORMAT('OWN2S:',7F9.1)
    WRITE(4,502) RNT13, RNT23, RNT24, HOLD, KP,KT,J,I, P4(KP,KT,J,I)
502 FORMAT('OWN2S:',4F9.1,12X,'P4(',I2,',',I2,',',I1,',',I2,')=',I2)
    END IF
    END
```

Exerpts from the Output File

```
Replacement with Renting Options
      60        16        32        16         0        20         0
  1.2000    1.1400    1.0700    1.0000     .0600         1
150.9000   63.2000  181.6000   63.2000  517.4400  352.8600
  9.2000   15.2000   27.2000
560.2671  595.8664         1         2
202.4880  234.1310     .6820     .4650
203.1760  235.0030   89.4750  107.6800
203.9190  235.9460   80.5280   96.9120
204.6940  236.9280   72.4750   87.2200
205.4920  237.9400   65.2270   78.4980
206.3080  238.9740   58.7050   70.6490
207.1400  240.0280   52.8340   63.5840
207.9840  241.0980   47.5510   57.2250
208.8400  242.1820   42.7960   51.5030
209.7050  243.2800   38.5160   46.3530
210.5800  244.3890   34.6640   41.7170
211.4640  245.5080   31.1980   37.5460
212.3550  246.6380   28.0780   33.7910
213.2530  247.7760   25.2700   30.4120
214.1580  248.9230   22.7430   27.3710
215.0690  250.0780   20.4690   24.6340
215.9860  251.2410   18.4220   22.1700
216.9090  252.4100   16.5800   19.9530
217.8370  253.5860   14.9220   17.9580
218.7700  254.7690   13.4300   16.1620
  2.1790    1.4860  338.1260  243.3960
  3.6320    2.4770  327.5590  231.1630
  5.0840    3.4670  316.9570  218.9850
  6.5370    4.4580  306.3430  206.9210
  7.9900    5.4490  295.7440  195.0240
  9.4420    6.4390  285.1820  183.3430
 10.8950    7.4300  274.6800  171.9230
 12.3480    8.4200  264.2600  160.8030
 13.8010    9.4110  253.9420  150.0200
 15.2530   10.4020  243.7450  139.6040
 16.7060   11.3920  233.6880  129.5810
 18.1590   12.3830  223.7870  119.9700
 19.6110   13.3740  214.0590  110.7900
 21.0640   14.3640  204.5170  102.0520
 22.5170   15.3550  195.1760   93.7640
 23.9690   16.3460  186.0460   85.9290
 25.4220   17.3360  177.1380   78.5490
 26.8750   18.3270  168.4630   71.6200
 28.3270   19.3180  160.0280   65.1360
 29.7800   20.3080  151.8390   59.0880
 31.2330   21.2990  143.9040   53.4650
 32.6850   22.2890  136.2260   48.2540
 34.1380   23.2800  128.8090   43.4400
 35.5910   24.2710  121.6550   39.0070
 37.0440   25.2610  114.7660   34.9370
 38.4960   26.2520  108.1420   31.2120
 39.9490   27.2430  101.7830   27.8130
 41.4020   28.2330   95.6880   24.7220
```

```
  42.8540  29.2240  89.8540  21.9180
  44.3070  30.2150  84.2780  19.3820
  45.7600  31.2050  78.9570  17.0960
  47.2120  32.1960  73.8860  15.0420
  48.6650  33.1870  69.0620  13.2000
  50.1180  34.1770  64.4780  11.5550
  51.5700  35.1680  60.1290  10.0890
  53.0230  36.1590  56.0080   8.7860
  54.4760  37.1490  52.1100   7.6330
  55.9290  38.1400  48.4270   6.6130
  57.3810  39.1300  44.9530   5.7160
  58.8340  40.1210  41.6790   4.9270
YEAR 60
YEAR 59
YEAR 58
YEAR 57
YEAR 56
      .
      .
      .
YEAR  3
YEAR  2
OWN1L::   65.66   21.15  174.73  228.13  185.59   27.83   76.94   61.82
OWN1L::  241.18  226.27   68.50   63.38  225.91     .00   10.36   31.09
OWN1L::  165.50  175.87  196.59   12.72   P1( 1, 1,1, 2)=14
OWN1L::   66.83   22.31  174.47  229.30  186.76   29.00   78.11   62.99
OWN1L::  242.35  227.43   69.67   63.40  225.93     .00   10.29   30.87
OWN1L::  165.50  175.79  196.37   12.79   P1( 2, 1,1, 2)=14
OWN1L::   67.70   23.19  174.32  230.17  187.63   29.87   78.99   63.86
OWN1L::  243.22  228.31   70.55   63.33  225.86     .00   10.21   30.63
OWN1L::   165.50   175.72   196.14    12.87   P1( 3, 1,1, 2)=14
OWN1L::   68.31   23.80  174.28  230.78  188.24   30.48   79.60   64.48
OWN1L::  243.83  228.92   71.16   63.18  225.71     .00   10.13   30.40
OWN1L::  165.50  175.64  195.90   12.95   P1( 4, 1,1, 2)=14
      .
      .
      .

OPT. POLICY STARTING WITH A16 YR. OLD PLANTER OF TYPE 1 AND LARGE
TRACTOR IS:

    YEAR:  1  PLANTER AGE:16  TRACTOR AGE:20  J: 1
IN YEAR  1 OWNING: 13  POLICY:  6   REPLACE W/ SMALL TCTR, PLTR 2.
    YEAR:  2  PLANTER AGE: 1  TRACTOR AGE: 1  J: 2
IN YEAR  2 OWNING: 24  POLICY: 11   KEEP BOTH MACHINES
    YEAR:  3  PLANTER AGE: 2  TRACTOR AGE: 2  J: 3
IN YEAR  3 OWNING: 24  POLICY: 11   KEEP BOTH MACHINES
    YEAR:  4  PLANTER AGE: 3  TRACTOR AGE: 3  J: 4
IN YEAR  4 OWNING: 24  POLICY: 11   KEEP BOTH MACHINES
    YEAR:  5  PLANTER AGE: 4  TRACTOR AGE: 4  J: 4
IN YEAR  5 OWNING: 24  POLICY: 11   KEEP BOTH MACHINES
    YEAR:  6  PLANTER AGE: 5  TRACTOR AGE: 5  J: 4
IN YEAR  6 OWNING: 24  POLICY: 11   KEEP BOTH MACHINES
    YEAR:  7  PLANTER AGE: 6  TRACTOR AGE: 6  J: 4
IN YEAR  7 OWNING: 24  POLICY: 11   KEEP BOTH MACHINES
    YEAR:  8  PLANTER AGE: 7  TRACTOR AGE: 7  J: 4
IN YEAR  8 OWNING: 24  POLICY: 11   KEEP BOTH MACHINES
```

Appendix H

FORTRAN CODE FOR THE STOCHASTIC DYNAMIC PROGRAMMING MODEL

This Appendix contains the FORTRAN code for the stochastic dynamic programming model that is used to determine optimal adoption strategies for the expected utility-maximizing farmer. Most of the variable names are the same as for the deterministic model, and are listed in Appendix G. Additional variable names are listed below. As in Appendix G, the statements or the parts of statements that do not conform to the FORTRAN 77 standard are shown in bold print.

The listed code is for the version of the model that does not include options to rent the no-till planter on a limited acreage. The version that does include these options calculates their value functions in a manner that is similar to what is listed in Appendix G.

The listed code also is for the version of the model that maximizes expected utility with the relative risk aversion coefficient equal to 1.0. The version of the model that is based on a relative risk aversion coefficient equal to 0.5 is identical, except that the "ALOG" function is replaced by "2.0*SQRT" in value function calculations.

Description of Additional Variable Names (in order of appearance)

AV	Risk aversion coefficient. This is no longer used. Log and square root functions are used instead of the CRRA utility function with exponent (1-AV).
RAV	Equals (1-AV). No longer used for the reason above.
VC1	Variable costs (Subtotal 1 in Table 4.10) on 600 acres for conventional tillage.
VC2	Variable costs (Subtotal 1 in Table 4.10) on 600 acres for no-till.
JL	Counter variable used for price state (previous year).
PP	Markovian price probabilities for current year's price state, based on previous year's price state.

JP	Counter variable used for current year's price state.
JC	Counter variable for crop. Corn = 1, Soybeans = 2.
JW	Counter variable for weather (and its effect on yield).
YC	Yield for each weather, technology, and crop combination.
JA	Counter variable used for technology option. Conventional tillage = 1, No-till = 2.
R	Gross revenue for each weather, technology, and crop price combination.
IP1	Optimal policy in year 1 (replaces P1 in determ. model).
WP	Probability weights for each combination of crop price and weather.
JN	Counter variable used for next year's price state.

The Program for the Stochastic Model

```
C     DP Stochastic Replacement Problem, including 2 planters,
C        2 tractors, renting, and experience with the 2nd planter.
C     This problem maximizes a CPRRA utility function with risk
C        aversion parameter equal to 1.
C     ******************************************************************
$STORAGE:2
      PROGRAM STORPLN
      CHARACTER*78 TITLE
      CHARACTER*32 POLICY
      INTEGER*1 N, MP, MT, IAGE1, IAGE2, IAGE3, IAGE4, KX
      REAL PR1, PR2, PR3, PR4, RNT1, RNT2, CN1, CN2, CN3, CN4
      REAL VL3(34,5,7), VL4(34,5,7), PC(2,7), YC(33,2,2)
      COMMON /REV/ PR1, PR2, PR3, PR4, RNT1, RNT2, R(7,33,2)
      COMMON /REV/ CN1, CN2, CN3, CN4, CX(4), C3(40), VC1, VC2
      COMMON /VALS/ A, PP(7,7)
      COMMON /VALS/ VN1(18,34,5,7), VN2(18,34,5,7)
      COMMON /VALS/ VN4(18,34,5,7), VLN3(34,5,7), VLN4(34,5,7)
      COMMON /OWN1/ C1(20), T1(20), S1(20), V1(18,34,5,7), IP1(7)
      COMMON /OWN2/ C2(20), T2(20), S2(20)
      COMMON /OWN3/ T3(40), S3(40)
      COMMON /OWN4/ C4(40), T4(40), S4(40)
      COMMON /OWN23/ V2(18,34,5,7)
      COMMON /OWN24/ V4(18,34,5,7)

      OPEN (UNIT = 2, FILE = 'STORP2.DAT')
      OPEN (UNIT = 4, FILE = 'STORPLN.OUT')
      READ(2,20) TITLE
   20 FORMAT(78A)
      WRITE(4,22) TITLE
   22 FORMAT(78A/)
      READ(2,25) N, MP, MT, IAGE1, IAGE2, IAGE3, IAGE4
      WRITE(4,25) N, MP, MT, IAGE1, IAGE2, IAGE3, IAGE4
   25 FORMAT(7I9)
      READ(2,30) CX(1), CX(2), CX(3), CX(4), DF, AV, KX
      WRITE(4,30) CX(1), CX(2), CX(3), CX(4), DF, AV, KX
   30 FORMAT(6F9.4,I9)
```

```
      READ(2,35) PR1, RNT1, PR2, RNT2, PR3, PR4
      WRITE(4,35) PR1, RNT1, PR2, RNT2, PR3, PR4
   35 FORMAT(6F9.2)
      KPI = IAGE1
      IF (IAGE2 .GT. IAGE1) KPI = IAGE2
      KTI = IAGE3
      IF (IAGE4 .GT. IAGE3) KTI = IAGE4
      NP1 = N+1
      MPP1 = MP+1
      MTP2 = MT+2
      A = 1.0 / (1.0 + DF)
      RAV = 1.0 - AV

C *** READ VARIABLE COST BASE (VCi) FOR MB PLOW AND NO-TILL
      READ(2,40) VC1, VC2
      WRITE(4,40) VC1, VC2
   40 FORMAT(2F9.2)

C *** READ COSTS AND TRADE-IN VALUES FOR PLANTERS AND TRACTORS
      READ(2,50) CN1, CN2, CN3, CN4
      WRITE(4,50) CN1, CN2, CN3, CN4
      DO 45 K=1,19
      READ(2,50) C1(K), C2(K), T1(K), T2(K)
      S1(K) = T1(K)
      S2(K) = T2(K)
   45 WRITE(4,50) C1(K), C2(K), T1(K), T2(K)
   50 FORMAT(4F9.1)
      DO 60 K=1,40
      READ(2,65) C3(K), C4(K), T3(K), T4(K)
      S3(K) = T3(K)
      S4(K) = T4(K)
   60 WRITE(4,65) C3(K), C4(K), T3(K), T4(K)
   65 FORMAT(4F9.1)

C *** READ PRICE STATE PROBABILITIES
      DO 67 JL=1,7
          READ(2,75) (PP(JL,JP), JP=1,7)
          WRITE(4,75) (PP(JL,JP), JP=1,7)
   67 CONTINUE
C *** READ CORN AND SOYBEAN PRICES FOR EACH PRICE STATE
      DO 72 JC=1,2
          READ(2,75) (PC(JC,JP), JP=1,7)
          WRITE(4,75) (PC(JC,JP), JP=1,7)
   72 CONTINUE
   75 FORMAT(7F9.2)
C *** READ CROP YIELDS FOR FALL PLOWING AND NO-TILL
C *** THE 33 OUTCOMES REPRESENT 1953-78, 1984-90.
      DO 77 JC=1,2
          DO 77 JW=1,33
              READ(2,79) (YC(JW,JA,JC), JA=1,2)
              WRITE(4,79) (YC(JW,JA,JC), JA=1,2)
   77 CONTINUE
   79 FORMAT(2F9.2)
      CLOSE (2)
```

```
      CALL GETTIM(IHR,IMIN,ISEC,I100TH)
      WRITE(4,'(3X, I2.2, 1H:, I2.2, 1H:, I2.2)') IHR, IMIN, ISEC

C *** SET PENALTIES TO LIMIT AGES OF PLANTERS AND TRACTORS
      DO 15 K=MPP1,20
      C1(K) = 30000.
      C2(K) = 30000.
      S1(K) = 1.
      S2(K) = 1.
      T1(K) = 1.
   15 T2(K) = 1.
      DO 16 K=MTP2,40
      C3(K) = 30000.
      C4(K) = 30000.
      S3(K) = 1.
      S4(K) = 1.
      T3(K) = 1.
   16 T4(K) = 1.

C *** SET REVENUES FOR PRICE, YIELD, AND TECH. COMBINATIONS
      DO 18 JP=1,7
         DO 18 JW=1,33
            DO 18 JA=1,2
               R(JP,JW,JA)=PC(1,JP)*YC(JW,JA,1)*400.0 +
     +                     PC(2,JP)*YC(JW,JA,2)*200.0 + 90000
  18  CONTINUE
C     ******************************************************************
C     SET TERMINAL PERIOD VALUE FUNCTIONS
C     ******************************************************************
      IF (KPI + MP .GT. 16) THEN
          MPPI = 16
          ELSE
              MPPI = MPP1
      END IF
      IF (KTI + MT .GT. 32) THEN
          MTPI = 32
              ELSE
                  MTPI = MTP2
      END IF

      DO 3 JP=1,7
         DO 3 J=1,5
            DO 3 KT=1,MTPI
                DO 2 KP=1,MPPI
                    VN1(KP,KT,J,JP) = ALOG(S1(KP)+S3(KT))
                    VN2(KP,KT,J,JP) = ALOG(S2(KP)+S3(KT))
    2               VN4(KP,KT,J,JP) = ALOG(S2(KP)+S4(KT))
                    VLN3(KT,J,JP) = ALOG(S3(KT))
                    VLN4(KT,J,JP) = ALOG(S4(KT))
    3 CONTINUE
C     ******************************************************************
C     BACKWARDS RECURSIVE CALCULATION OF THE VALUE FUNCTION AND POLICIES
C     ******************************************************************
      DO 8 II = 1,N
```

```
          I = N - II + 1
          IM1 = N - II
          JM1 = IM1 * 2
          IF (IM1 .GT. MPP1) IM1 = MPP1
          IF (JM1 .GT. MTP2) JM1 = MTP2
          IHI = IM1 + KPI
          JHI = JM1 + KTI
          IF (IHI .GT. MPP1) IHI = MPP1
          IF (JHI .GT. MTP2) JHI = MTP2
          WRITE(*,88) I
 88       FORMAT('    YEAR ',I2)
          DO 6 JL=1,7
             DO 6 J=1,4
                 WRITE(*,605) JL, J
                 DO 6 KT=1,JHI
                     CALL DECL3(KT, J, JL, VL3)
                     CALL DECL4(KT, J, JL, VL4)
                     DO 6 KP = 1,IHI
                           CALL DECO1(KP, KT, J, JL, I)
                           CALL DECO2(KP, KT, J, JL)
                           CALL DECO4(KP, KT, J, JL)
  6       CONTINUE
605       FORMAT(4X,'JL=',I3,3X,'J=',I3)

C *** RESET THE NEXT PERIOD VALUE FUNCTIONS
         DO 36 JL=1,7
             DO 36 KT=1,JHI
                 DO 38 J=1,4
                    VLN3(KT,J,JL) = VL3(KT,J,JL)
 38                 VLN4(KT,J,JL) = VL4(KT,J,JL)
                    VLN3(KT,5,JL) = VL3(KT,4,JL)
                    VLN4(KT,5,JL) = VL4(KT,4,JL)
                    DO 36 KP=1,IHI
                       DO 39 J=1,4
                           VN1(KP,KT,J,JL) = V1(KP,KT,J,JL)
                           VN2(KP,KT,J,JL) = V2(KP,KT,J,JL)
 39                        VN4(KP,KT,J,JL) = V4(KP,KT,J,JL)
                           VN1(KP,KT,5,JL) = V1(KP,KT,4,JL)
                           VN2(KP,KT,5,JL) = V2(KP,KT,4,JL)
                           VN4(KP,KT,5,JL) = V4(KP,KT,4,JL)
 36      CONTINUE

  8  CONTINUE
C    ************************************************************************
C    REPORT THE OPTIMAL POLICIES FOR EACH PRICE STATE IN YEAR 1
C    ************************************************************************
     KP = KPI
     KT = KTI
         WRITE(4,90) KP, KT
 90  FORMAT('  OPT. POLICIES FOR A ',I2,' YEAR OLD PLANTER AND A ',I2,
    +' YEAR OLD TRACTOR ARE:',/)

     DO 10 JL=1,7
             IF (IP1(JL) .EQ. 1) THEN
```

```
                POLICY = 'REPLACE PLANTER 1'
          ELSE IF (IP1(JL) .EQ. 2) THEN
                POLICY = 'REPLACE W/ PLANTER 2'
          ELSE IF (IP1(JL) .EQ. 3) THEN
                POLICY = 'REPLACE LARGE TRACTOR'
          ELSE IF (IP1(JL) .EQ. 4) THEN
                POLICY = 'REPLACE BOTH MACHINES'
          ELSE IF (IP1(JL) .EQ. 5) THEN
                POLICY = 'REPLACE W/ LARGE TCTR, PLTR 2.'
          ELSE IF (IP1(JL) .EQ. 6) THEN
                POLICY = 'REPLACE W/ SMALL TCTR, PLTR 2.'
          ELSE IF (IP1(JL) .EQ. 7) THEN
                POLICY = 'RENT PLANTER 1'
          ELSE IF (IP1(JL) .EQ. 8) THEN
                POLICY = 'RENT PLANTER 2'
          ELSE IF (IP1(JL) .EQ. 9) THEN
                POLICY = 'REPLACE L. TCTR., RENT PLTR. 1'
          ELSE IF (IP1(JL) .EQ. 10) THEN
                POLICY = 'REPLACE L. TCTR., RENT PLTR. 2'
          ELSE IF (IP1(JL) .EQ. 11) THEN
                POLICY = 'RPLCE W/SMALL TCTR. RENT PLTR 2'
          ELSE IF (IP1(JL) .EQ. 12) THEN
                POLICY = 'RENT PLANTER 1, KEEP PLANTER 2'
          ELSE IF (IP1(JL) .EQ. 13) THEN
                POLICY = 'RPLCE TCTR, RNT PLTR 2, KEEP 1'
          ELSE IF (IP1(JL) .EQ. 14) THEN
                POLICY = 'KEEP BOTH MACHINES'
          END IF

      WRITE(4,95) IP1(JL), POLICY
 95   FORMAT('   POLICY:--',I2,3X,A32)
      WRITE(4,98) V1(KP,KT,KX,JL)
 98   FORMAT('   EXPECTED UTILITY VALUE: ',E20.10)

 10   CONTINUE

      CALL GETTIM(IHR,IMIN,ISEC,I100TH)
      WRITE(4,'(3X, I2.2, 1H:, I2.2, 1H:, I2.2)') IHR, IMIN, ISEC
      CLOSE (4)

 2000 END

      SUBROUTINE DECL3 (KT, J, JL, VL3)
      REAL VL3(34,5,7), WP(7)
      COMMON /REV/ PR1, PR2, PR3, PR4, RNT1, RNT2, R(7,33,2)
      COMMON /REV/ CN1, CN2, CN3, CN4, CX(4), C3(40), VC1, VC2
      COMMON /VALS/ A, PP(7,7)
      COMMON /VALS/ VN1(18,34,5,7), VN2(18,34,5,7)
      COMMON /VALS/ VN4(18,34,5,7), VLN3(34,5,7), VLN4(34,5,7)
      COMMON /OWN3/ T3(40), S3(40)

C *** CALCULATION OF CONSTANT VALUES FOR EACH ALTERNATIVE

      BY1B = PR1 + CN1 + C3(KT) + C3(KT+1) + VC1
```

```
      BY2B = PR2 + (CN2 + C3(KT))*CX(J) + VC2
      CR1B = RNT1 + CN1 + C3(KT) + C3(KT+1) + VC1
      CR2B = RNT2 + (CN2 + C3(KT))*CX(J) + VC2
      B13B = PR1 + PR3 - T3(KT) + CN1 + CN3 + C3(1) + VC1
      B23B = PR2 + PR3 - T3(KT) + (CN2 + CN3)*CX(J) + VC2
      B24B = PR2 + PR4 - T3(KT) + (CN2 + CN4)*CX(J) + VC2
      C31B = PR3 - T3(KT) + RNT1 + CN1 + CN3 + C3(1) + VC1
      C32B = PR3 - T3(KT) + RNT2 + (CN2 + CN3)*CX(J) + VC2

      BY1 = 0.0
      BY2 = 0.0
      CR1 = 0.0
      CR2 = 0.0
      BY13 = 0.0
      BY23 = 0.0
      BY24 = 0.0
      CR31 = 0.0
      CR32 = 0.0

C *** DETERMINE PROBABILITY WEIGHTS
      DO 160 JP=1,7
 160          WP(JP) = PP(JL,JP)/33.0

      DO 130 JP=1,7
          IF (WP(JP) .GT. 0.0) THEN
          DO 120 JW=1,33

              BY1  = BY1+WP(JP)*ALOG(R(JP,JW,1)-BY1B)
              CR1  = CR1+WP(JP)*ALOG(R(JP,JW,1)-CR1B)
              BY13 = BY13+WP(JP)*ALOG(R(JP,JW,1)-BY1B)
              CR31 = CR31+WP(JP)*ALOG(R(JP,JW,1)-C31B)

              BY2  = BY2+WP(JP)*ALOG(R(JP,JW,2)-BY2B)
              CR2  = CR2+WP(JP)*ALOG(R(JP,JW,2)-CR2B)
              BY23 = BY23+WP(JP)*ALOG(R(JP,JW,2)-B23B)
              BY24 = BY24+WP(JP)*ALOG(R(JP,JW,2)-B23B)
              CR32 = CR32+WP(JP)*ALOG(R(JP,JW,2)-C32B)

 120      CONTINUE
          END IF
 130  CONTINUE

      DO 140 JP=1,7
          DO 140 JN = 1,7
              BY1 = BY1 + A*VN1(1,KT+2,J,JP)*PP(JP,JN)*PP(JL,JP)
              CR1 = CR1 + A*VLN3(KT+2,J,JP)*PP(JP,JN)*PP(JL,JP)
              BY13 = BY13 + A*VN1(1,2,J,JP)*PP(JP,JN)*PP(JL,JP)
              CR31 = CR31 + A*VLN3(2,J,JP)*PP(JP,JN)*PP(JL,JP)
              BY2 = BY2 + A*VN2(1,KT+1,J+1,JP)*PP(JP,JN)*PP(JL,JP)
              CR2 = CR2 + A*VLN3(KT+1,J+1,JP)*PP(JP,JN)*PP(JL,JP)
              BY23 = BY23 + A*VN2(1,1,J+1,JP)*PP(JP,JN)*PP(JL,JP)
              BY24 = BY24 + A*VN4(1,1,J+1,JP)*PP(JP,JN)*PP(JL,JP)
              CR32 = CR32 + A*VLN3(1,J+1,JP)*PP(JP,JN)*PP(JL,JP)
 140  CONTINUE
```

```
      CB = AMAX1(BY1,BY2,BY13,BY23,BY24)
      CR = AMAX1(CR1,CR2,CR31,CR32)
      VL3(KT,J,JL) = AMAX1(CB,CR)
      END

      SUBROUTINE DECL4 (KT, J, JL, VL4)
      REAL VL4(34,5,7), WP(7)
      COMMON /REV/ PR1, PR2, PR3, PR4, RNT1, RNT2, R(7,33,2)
      COMMON /REV/ CN1, CN2, CN3, CN4, CX(4), C3(40), VC1, VC2
      COMMON /VALS/ A, PP(7,7)
      COMMON /VALS/ VN1(18,34,5,7), VN2(18,34,5,7)
      COMMON /VALS/ VN4(18,34,5,7), VLN3(34,5,7), VLN4(34,5,7)
      COMMON /OWN4/ C4(40), T4(40), S4(40)

C *** CALCULATION OF CONSTANT VALUES FOR EACH ALTERNATIVE

      BY2B = PR2 + (CN2 + C4(KT))*CX(J) + VC2
      CR2B = RNT2 + (CN2 + C4(KT))*CX(J) + VC2
      B13B = PR1 + PR3 - T4(KT) + CN1 + CN3 + C3(1) + VC1
      B23B = PR2 + PR3 - T4(KT) + (CN2 + CN3)*CX(J) + VC2
      B24B = PR2 + PR4 - T4(KT) + (CN2 + CN4)*CX(J) + VC2
      C42B = PR3 - T4(KT) + RNT2 + (CN2 + CN4)*CX(J) + VC2

      BY2 = 0.0
      CR2 = 0.0
      BY13 = 0.0
      BY23 = 0.0
      BY24 = 0.0
      CR42 = 0.0

C *** DETERMINE PROBABILITY WEIGHTS
      DO 260 JP=1,7
 260          WP(JP) = PP(JL,JP)/33.0

      DO 230 JP=1,7
          IF (WP(JP) .GT. 0.0) THEN
          DO 220 JW=1,33

              BY13 = BY13+WP(JP)*ALOG(R(JP,JW,1)-B13B)

              BY2  = BY2+WP(JP)*ALOG(R(JP,JW,2)-BY2B)
              CR2  = CR2+WP(JP)*ALOG(R(JP,JW,2)-CR2B)
              BY23 = BY23+WP(JP)*ALOG(R(JP,JW,2)-B23B)
              BY24 = BY24+WP(JP)*ALOG(R(JP,JW,2)-B24B)
              CR42 = CR42+WP(JP)*ALOG(R(JP,JW,2)-C42B)

 220      CONTINUE
          END IF
 230  CONTINUE

      DO 240 JP=1,7
         DO 240 JN=1,7
            BY13 = BY13 + A*VN1(1,2,J,JN)*PP(JP,JN)*PP(JL,JP)
            BY2 = BY2 + A*VN4(1,KT+1,J+1,JN)*PP(JP,JN)*PP(JL,JP)
```

```
            CR2 = CR2 + A*VLN4(KT+1,J+1,JN)*PP(JP,JN)*PP(JL,JP)
            BY23 = BY23 + A*VN2(1,1,J+1,JN)*PP(JP,JN)*PP(JL,JP)
            BY24 = BY24 + A*VN4(1,1,J+1,JN)*PP(JP,JN)*PP(JL,JP)
            CR42 = CR42 + A*VLN4(1,J+1,JN)*PP(JP,JN)*PP(JL,JP)
 240  CONTINUE

      VL4(KT,J,JL) = AMAX1(BY2,BY13,BY23,BY24,CR2,CR42)
      END

      SUBROUTINE DEC01 (KP, KT, J, JL, I)
      REAL WP(7)
      COMMON /REV/ PR1, PR2, PR3, PR4, RNT1, RNT2, R(7,33,2)
      COMMON /REV/ CN1, CN2, CN3, CN4, CX(4), C3(40), VC1, VC2
      COMMON /VALS/ A, PP(7,7)
      COMMON /VALS/ VN1(18,34,5,7), VN2(18,34,5,7)
      COMMON /VALS/ VN4(18,34,5,7), VLN3(34,5,7), VLN4(34,5,7)
      COMMON /OWN1/ C1(20), T1(20), S1(20), V1(18,34,5,7), IP1(7)
      COMMON /OWN3/ T3(40), S3(40)

C *** CALCULATION OF CONSTANT VALUES FOR EACH ALTERNATIVE

      RP1B = PR1 - T1(KP) + CN1 + C3(KT) + C3(KT+1) + VC1
      RP2B = PR2 - T1(KP) + (CN2 + C3(KT))*CX(J) + VC2
      RP3B = PR3 - T3(KT) + C1(KP) + CN3 + C3(1) + VC1
      RP13B = PR1 + PR3 - T1(KP) - T3(KT) + CN1 + CN3 + C3(1) + VC1
      RP23B = PR2 + PR3 - T1(KP) - T3(KT) + (CN2 + CN3)*CX(J) + VC2
      RP24B = PR2 + PR4 - T1(KP) - T3(KT) + (CN2 + CN4)*CX(J) + VC2
      RT1B = -S1(KP) + RNT1 + CN1 + C3(KT) + C3(KT+1) + VC1
      RT2B = -S1(KP) + RNT2 + (CN2 + C3(KT))*CX(J) + VC2
      R13B = -S1(KP) - T3(KT) + PR3 + RNT1 + CN1 + CN3 + C3(1) + VC1
      R23B = -S1(KP) - T3(KT) + PR3 + RNT2 + (CN2 + CN3)*CX(J) + VC2
      R24B = -S1(KP) - T3(KT) + PR4 + RNT2 + (CN2 + CN4)*CX(J) + VC2
      R2KB = RNT2 + (CN2 + C3(KT))*CX(J) + VC2
      R23KB = RNT2 + PR3 - T3(KT) + (CN2 + CN3)*CX(J) + VC2
      HOLDB = C1(KP) + C3(KT) + C3(KT+1) + VC1

      RP1 = 0.0
      RP2 = 0.0
      RP3 = 0.0
      RP13 = 0.0
      RP23 = 0.0
      RP24 = 0.0
      RT1 = 0.0
      RT2 = 0.0
      RT13 = 0.0
      RT23 = 0.0
      RT24 = 0.0
      RT2K = 0.0
      RT23K = 0.0
      HOLD = 0.0

C *** DETERMINE PROBABILITY WEIGHTS
      DO 360 JP=1,7
 360        WP(JP) = PP(JL,JP)/33.0
```

```
      DO 330 JP=1,7
          IF (WP(JP) .GT. 0.0) THEN
          DO 320 JW=1,33

              RP1 = RP1+WP(JP)*ALOG(R(JP,JW,1)-RP1B)
              RP3 = RP3+WP(JP)*ALOG(R(JP,JW,1)-RP3B)
              RP13 = RP13+WP(JP)*ALOG(R(JP,JW,1)-RP13B)
              RT1 = RT1+WP(JP)*ALOG(R(JP,JW,1)-RT1B)
              RT13 = RT13+WP(JP)*ALOG(R(JP,JW,1)-R13B)
              HOLD = HOLD+WP(JP)*ALOG(R(JP,JW,1)-HOLDB)

              RP2 = RP2+WP(JP)*ALOG(R(JP,JW,2)-RP2B)
              RP23 = RP23+WP(JP)*ALOG(R(JP,JW,2)-RP23B)
              RP24 = RP24+WP(JP)*ALOG(R(JP,JW,2)-RP24B)
              RT2 = RT2+WP(JP)*ALOG(R(JP,JW,2)-RT2B)
              RT23 = RT23+WP(JP)*ALOG(R(JP,JW,2)-R23B)
              RT24 = RT24+WP(JP)*ALOG(R(JP,JW,2)-R24B)
              RT2K = RT2K+WP(JP)*ALOG(R(JP,JW,2)-R2KB)
              RT23K = RT23K+WP(JP)*ALOG(R(JP,JW,2)-R23KB)

320       CONTINUE
          END IF
330   CONTINUE

      DO 340 JP=1,7
        DO 340 JN=1,7
          RP1 = RP1 + A*VN1(1,KT+2,J,JN)*PP(JP,JN)*PP(JL,JP)
          RP3 = RP3 + A*VN1(KP+1,2,J,JN)*PP(JP,JN)*PP(JL,JP)
          RP13 = RP13 + A*VN1(1,2,J,JN)*PP(JP,JN)*PP(JL,JP)
          RT1 = RT1 + A*VLN3(KT+2,J,JN)*PP(JP,JN)*PP(JL,JP)
          RT13 = RT13 + A*VLN3(2,J,JN)*PP(JP,JN)*PP(JL,JP)
          HOLD = HOLD + A*VN1(KP+1,KT+2,J,JN)*PP(JP,JN)*PP(JL,JP)
          RP2 = RP2 + A*VN2(1,KT+1,J+1,JN)*PP(JP,JN)*PP(JL,JP)
          RP23 = RP23 + A*VN2(1,1,J+1,JN)*PP(JP,JN)*PP(JL,JP)
          RP24 = RP24 + A*VN4(1,1,J+1,JN)*PP(JP,JN)*PP(JL,JP)
          RT2 = RT2 + A*VLN3(KT+1,J+1,JN)*PP(JP,JN)*PP(JL,JP)
          RT23 = RT23 + A*VLN3(1,J+1,JN)*PP(JP,JN)*PP(JL,JP)
          RT24 = RT24 + A*VLN4(1,J+1,JN)*PP(JP,JN)*PP(JL,JP)
          RT2K = RT2K + A*VN1(KP,KT+1,J+1,JN)*PP(JP,JN)*PP(JL,JP)
          RT23K = RT23K + A*VN1(KP,1,J+1,JN)*PP(JP,JN)*PP(JL,JP)
340   CONTINUE

      CB = AMAX1(RP1,RP2,RP3,RP13,RP23,RP24,HOLD)
      CR = AMAX1(RT1,RT2,RT13,RT23,RT24,RT2K,RT23K)
      V1(KP,KT,J,JL) = AMAX1(CB,CR)

      IF (KP .EQ. 1 .AND. KT .EQ. 2) THEN
      WRITE(*,365) RP2, RP24, RT2, HOLD
      END IF
365   FORMAT(4(2X,E12.7))

      IF (I .EQ. 1 .AND. J .EQ. 1) THEN
          IF (V1(KP,KT,J,JL) .EQ. RP1) IP1(JL) = 1
          IF (V1(KP,KT,J,JL) .EQ. RP2) IP1(JL) = 2
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          IF (V1(KP,KT,J,JL) .EQ. RP3) IP1(JL) = 3
          IF (V1(KP,KT,J,JL) .EQ. RP13) IP1(JL) = 4
          IF (V1(KP,KT,J,JL) .EQ. RP23) IP1(JL) = 5
          IF (V1(KP,KT,J,JL) .EQ. RP24) IP1(JL) = 6
          IF (V1(KP,KT,J,JL) .EQ. RT1) IP1(JL) = 7
          IF (V1(KP,KT,J,JL) .EQ. RT2) IP1(JL) = 8
          IF (V1(KP,KT,J,JL) .EQ. RT13) IP1(JL) = 9
          IF (V1(KP,KT,J,JL) .EQ. RT23) IP1(JL) = 10
          IF (V1(KP,KT,J,JL) .EQ. RT24) IP1(JL) = 11
          IF (V1(KP,KT,J,JL) .EQ. RT2K) IP1(JL) = 12
          IF (V1(KP,KT,J,JL) .EQ. RT23K) IP1(JL) = 13
          IF (V1(KP,KT,J,JL) .EQ. HOLD) IP1(JL) = 14

          DRPL1 = V1(KP,KT,J,JL) - RP1
          DRPL2 = V1(KP,KT,J,JL) - RP2
          DRPL3 = V1(KP,KT,J,JL) - RP3
          DRPL13 = V1(KP,KT,J,JL) - RP13
          DRPL23 = V1(KP,KT,J,JL) - RP23
          DRPL24 = V1(KP,KT,J,JL) - RP24
          DRNT1 = V1(KP,KT,J,JL) - RT1
          DRNT2 = V1(KP,KT,J,JL) - RT2
          DRNT13 = V1(KP,KT,J,JL) - RT13
          DRNT23 = V1(KP,KT,J,JL) - RT23
          DRNT24 = V1(KP,KT,J,JL) - RT24
          DRNT2K = V1(KP,KT,J,JL) - RT2K
          DRT23K = V1(KP,KT,J,JL) - RT23K
          DHOLD = V1(KP,KT,J,JL) - HOLD

      WRITE(4,301) DRPL1, DRPL2, DRPL3, DRPL13, DRPL23, DRPL24
  301 FORMAT(' ',6F11.5)
      WRITE(4,302) DRNT1, DRNT2, DRNT13, DRNT23, DRNT24
  302 FORMAT(' ',5F11.5)
      WRITE(4,303) DRNT2K, DRT23K, DHOLD, V1(KP,KT,J,JL), KP, KT,
     + JL, IP1(JL)
  303 FORMAT(' ',4F11.5,4I4)
      END IF
      END

      SUBROUTINE DECO2 (KP, KT, J, JL)
      REAL WP(7)
      COMMON /REV/ PR1, PR2, PR3, PR4, RNT1, RNT2, R(7,33,2)
      COMMON /REV/ CN1, CN2, CN3, CN4, CX(4), C3(40), VC1, VC2
      COMMON /VALS/ A, PP(7,7)
      COMMON /VALS/ VN1(18,34,5,7), VN2(18,34,5,7)
      COMMON /VALS/ VN4(18,34,5,7), VLN3(34,5,7), VLN4(34,5,7)
      COMMON /OWN2/ C2(20), T2(20), S2(20)
      COMMON /OWN3/ T3(40), S3(40)
      COMMON /OWN23/ V2(18,34,5,7)

C *** CALCULATION OF CONSTANT VALUES FOR EACH ALTERNATIVE

      RP1B = PR1 - T2(KP) + CN1 + C3(KT) + C3(KT+1) + VC1
      RP2B = PR2 - T2(KP) + (CN2 + C3(KT))*CX(J) + VC2
      RP3B = PR3 - T3(KT) + (C2(KP) + CN3)*CX(J) + VC2
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```
      RP4B = PR3 - T3(KT) + (C2(KP) + CN4)*CX(J) + VC2
      RP13B = PR1 + PR3 - T2(KP) - T3(KT) + CN1 + CN3 + C3(1) + VC1
      RP23B = PR2 + PR3 - T2(KP) - T3(KT) + (CN2 + CN3)*CX(J) + VC2
      RP24B = PR2 + PR4 - T2(KP) - T3(KT) + (CN2 + CN4)*CX(J) + VC2
      RT1B = -S2(KP) + RNT1 + CN1 + C3(KT) + C3(KT+1) + VC1
      RT2B = -S2(KP) + RNT2 + (CN2 + C3(KT))*CX(J) + VC2
      R13B = -S2(KP) - T3(KT) + PR3 + RNT1 + CN1 + CN3 + C3(1) + VC1
      R23B = -S2(KP) - T3(KT) + PR3 + RNT2 + (CN2 + CN3)*CX(J) + VC2
      R24B = -S2(KP) - T3(KT) + PR4 + RNT2 + (CN2 + CN4)*CX(J) + VC2
      HOLDB = (C2(KP) + C3(KT))*CX(J) + VC2

      RP1 = 0.0
      RP2 = 0.0
      RP3 = 0.0
      RP4 = 0.0
      RP13 = 0.0
      RP23 = 0.0
      RP24 = 0.0
      RT1 = 0.0
      RT2 = 0.0
      RT13 = 0.0
      RT23 = 0.0
      RT24 = 0.0
      HOLD = 0.0

C *** DETERMINE PROBABILITY WEIGHTS
      DO 460 JP=1,7
 460          WP(JP) = PP(JL,JP)/33.0

      DO 430 JP=1,7
          IF (WP(JP) .GT. 0.0) THEN
          DO 420 JW=1,33

              RP1 = RP1+WP(JP)*ALOG(R(JP,JW,1)-RP1B)
              RP13 = RP13+WP(JP)*ALOG(R(JP,JW,1)-RP13B)
              RT1 = RT1+WP(JP)*ALOG(R(JP,JW,1)-RT1B)
              RT13 = RT13+WP(JP)*ALOG(R(JP,JW,1)-R13B)

              RP2 = RP2+WP(JP)*ALOG(R(JP,JW,2)-RP2B)
              RP3 = RP3+WP(JP)*ALOG(R(JP,JW,2)-RP3B)
              RP4 = RP4+WP(JP)*ALOG(R(JP,JW,2)-RP4B)
              RP23 = RP23+WP(JP)*ALOG(R(JP,JW,2)-RP23B)
              RP24 = RP24+WP(JP)*ALOG(R(JP,JW,2)-RP24B)
              RT2 = RT2+WP(JP)*ALOG(R(JP,JW,2)-RT2B)
              RT23 = RT23+WP(JP)*ALOG(R(JP,JW,2)-R23B)
              RT24 = RT24+WP(JP)*ALOG(R(JP,JW,2)-R24B)
              HOLD = HOLD+WP(JP)*ALOG(R(JP,JW,2)-HOLDB)

 420      CONTINUE
          END IF
 430  CONTINUE

      DO 440 JP=1,7
        DO 440 JN=1,7
```

```
      RP1 = RP1 + A*VN1(1,KT+2,J,JN)*PP(JP,JN)*PP(JL,JP)
      RP13 = RP13 + A*VN1(1,2,J,JN)*PP(JP,JN)*PP(JL,JP)
      RT1 = RT1 + A*VLN3(KT+2,J,JN)*PP(JP,JN)*PP(JL,JP)
      RT13 = RT13 + A*VLN3(2,J,JN)*PP(JP,JN)*PP(JL,JP)
      RP2 = RP2 + A*VN2(1,KT+1,J+1,JN)*PP(JP,JN)*PP(JL,JP)
      RP3 = RP3 + A*VN2(KP+1,1,J+1,JN)*PP(JP,JN)*PP(JL,JP)
      RP4 = RP4 + A*VN4(KP+1,1,J+1,JN)*PP(JP,JN)*PP(JL,JP)
      RP23 = RP23 + A*VN2(1,1,J+1,JN)*PP(JP,JN)*PP(JL,JP)
      RP24 = RP24 + A*VN4(1,1,J+1,JN)*PP(JP,JN)*PP(JL,JP)
      RT2 = RT2 + A*VLN3(KT+1,J+1,JN)*PP(JP,JN)*PP(JL,JP)
      RT23 = RT23 + A*VLN3(1,J+1,JN)*PP(JP,JN)*PP(JL,JP)
      RT24 = RT24 + A*VLN4(1,J+1,JN)*PP(JP,JN)*PP(JL,JP)
      HOLD = HOLD + A*VN2(KP+1,KT+1,J+1,JN)*PP(JP,JN)*PP(JL,JP)
440   CONTINUE

      CB = AMAX1(RP1,RP2,RP3,RP4,RP13,RP23,RP24,HOLD)
      CR = AMAX1(RT1,RT2,RT13,RT23,RT24)
      V2(KP,KT,J,JL) = AMAX1(CB,CR)
      END

      SUBROUTINE DECO4 (KP, KT, J, JL)
      REAL WP(7)
      COMMON /REV/ PR1, PR2, PR3, PR4, RNT1, RNT2, R(7,33,2)
      COMMON /REV/ CN1, CN2, CN3, CN4, CX(4), C3(40), VC1, VC2
      COMMON /VALS/ A, PP(7,7)
      COMMON /VALS/ VN1(18,34,5,7), VN2(18,34,5,7)
      COMMON /VALS/ VN4(18,34,5,7), VLN3(34,5,7), VLN4(34,5,7)
      COMMON /OWN2/ C2(20), T2(20), S2(20)
      COMMON /OWN4/ C4(40), T4(40), S4(40)
      COMMON /OWN24/ V4(18,34,5,7)

C *** CALCULATION OF CONSTANT VALUES FOR EACH ALTERNATIVE

      RP2B = PR2 - T2(KP) + (CN2 + C4(KT))*CX(J) + VC2
      RP3B = PR3 - T4(KT) + (C2(KP) + CN3)*CX(J) + VC2
      RP4B = PR3 - T4(KT) + (C2(KP) + CN4)*CX(J) + VC2
      RP13B = PR1 + PR3 - T2(KP) - T4(KT) + CN1 + CN3 + C3(1) + VC1
      RP23B = PR2 + PR3 - T2(KP) - T4(KT) + (CN2 + CN3)*CX(J) + VC2
      RP24B = PR2 + PR4 - T2(KP) - T4(KT) + (CN2 + CN4)*CX(J) + VC2
      RT2B = -S2(KP) + RNT2 + (CN2 + C4(KT))*CX(J) + VC2
      R13B = -S2(KP) - T4(KT) + PR3 + RNT1 + CN1 + CN3 + C3(1) + VC1
      R23B = -S2(KP) - T4(KT) + PR3 + RNT2 + (CN2 + CN3)*CX(J) + VC2
      R24B = -S2(KP) - T4(KT) + PR4 + RNT2 + (CN2 + CN4)*CX(J) + VC2
      HOLDB = (C2(KP) + C4(KT))*CX(J) + VC2

      RP2 = 0.0
      RP3 = 0.0
      RP4 = 0.0
      RP13 = 0.0
      RP23 = 0.0
      RP24 = 0.0
      RT2 = 0.0
      RT13 = 0.0
      RT23 = 0.0
```

```
      RT24 = 0.0
      HOLD = 0.0

C *** DETERMINE PROBABILITY WEIGHTS
      DO 560 JP=1,7
 560          WP(JP) = PP(JL,JP)/33.0

      DO 530 JP=1,7
          IF (WP(JP) .GT. 0.0) THEN
          DO 520 JW=1,33

              RP13 = RP13+WP(JP)*ALOG(R(JP,JW,1)-RP13B)
              RT13 = RT13+WP(JP)*ALOG(R(JP,JW,1)-R13B)

              RP2 = RP2+WP(JP)*ALOG(R(JP,JW,2)-RP2B)
              RP3 = RP3+WP(JP)*ALOG(R(JP,JW,2)-RP3B)
              RP4 = RP4+WP(JP)*ALOG(R(JP,JW,2)-RP4B)
              RP23 = RP23+WP(JP)*ALOG(R(JP,JW,2)-RP23B)
              RP24 = RP24+WP(JP)*ALOG(R(JP,JW,2)-RP24B)
              RT2 = RT2+WP(JP)*ALOG(R(JP,JW,2)-RT2B)
              RT23 = RT23+WP(JP)*ALOG(R(JP,JW,2)-R23B)
              RT24 = RT24+WP(JP)*ALOG(R(JP,JW,2)-R24B)
              HOLD = HOLD+WP(JP)*ALOG(R(JP,JW,2)-HOLDB)

 520      CONTINUE
          END IF
 530  CONTINUE

      DO 540 JP=1,7
        DO 540 JN=1,7
          RP13 = RP13 + A*VN1(1,2,J,JN)*PP(JP,JN)*PP(JL,JP)
          RT13 = RT13 + A*VLN3(2,J,JN)*PP(JP,JN)*PP(JL,JP)
          RP2 = RP2 + A*VN4(1,KT+1,J+1,JN)*PP(JP,JN)*PP(JL,JP)
          RP3 = RP3 + A*VN2(KP+1,1,J+1,JN)*PP(JP,JN)*PP(JL,JP)
          RP4 = RP4 + A*VN4(KP+1,1,J+1,JN)*PP(JP,JN)*PP(JL,JP)
          RP23 = RP23 + A*VN2(1,1,J+1,JN)*PP(JP,JN)*PP(JL,JP)
          RP24 = RP24 + A*VN4(1,1,J+1,JN)*PP(JP,JN)*PP(JL,JP)
          RT2 = RT2 + A*VLN4(KT+1,J+1,JN)*PP(JP,JN)*PP(JL,JP)
          RT23 = RT23 + A*VLN3(1,J+1,JN)*PP(JP,JN)*PP(JL,JP)
          RT24 = RT24 + A*VLN4(1,J+1,JN)*PP(JP,JN)*PP(JL,JP)
          HOLD = HOLD + A*VN4(KP+1,KT+1,J+1,JN)*PP(JP,JN)*PP(JL,JP)
 540  CONTINUE

      CB = AMAX1(RP2,RP3,RP4,RP13,RP23,RP24,HOLD)
      CR = AMAX1(RT2,RT13,RT23,RT24)
      V4(KP,KT,J,JL) = AMAX1(CB,CR)
      END
```

Exerpts from the Output File

Stochastic Replacement Analysis, RAV = 1.0

30	16	32	17	0	24	0
1.2000	1.1400	1.0700	1.0000	.0600	.5000	1
15090.00	6320.00	18160.00	6320.00	51744.00	35286.00	
58682.82	57014.16					
20248.8	23413.1	68.2	46.5			
20317.6	23500.3	8947.5	10768.0			
20391.9	23594.6	8052.8	9691.2			
20469.4	23692.8	7247.5	8722.0			
20549.2	23794.0	6522.7	7849.8			
20630.8	23897.4	5870.5	7064.9			
20714.0	24002.8	5283.4	6358.4			
20798.4	24109.8	4755.1	5722.5			
20884.0	24218.2	4279.6	5150.3			
20970.5	24328.0	3851.6	4635.3			
21058.0	24438.9	3466.4	4171.7			
.						
.						
.						
4576.0	3120.5	7895.7	1709.6			
4721.2	3219.6	7388.6	1504.2			
4866.5	3318.7	6906.2	1320.0			
5011.8	3417.7	6447.8	1155.5			
5157.0	3516.8	6012.9	1008.9			
5302.3	3615.9	5600.8	878.6			
5447.6	3714.9	5211.0	763.3			
5592.9	3814.0	4842.7	661.3			
5738.1	3913.0	4495.3	571.6			
5883.4	4012.1	4167.9	492.7			
.70	.10	.08	.12	.00	.00	.00
.10	.23	.22	.15	.15	.00	.15
.22	.18	.40	.20	.00	.00	.00
.08	.20	.10	.40	.07	.07	.08
.18	.10	.00	.15	.20	.20	.17
.15	.00	.15	.15	.15	.15	.25
.00	.00	.00	.05	.05	.20	.70
2.18	2.18	2.62	2.62	2.62	3.59	3.59
5.63	6.65	5.63	6.65	10.08	6.65	10.08
112.81	114.38					
63.33	68.09					
103.82	106.15					
117.84	112.83					
142.07	131.69					
154.23	160.39					
134.43	131.94					
99.81	101.54					
101.49	105.11					
62.26	61.75					
128.13	134.61					
103.33	107.43					
49.48	51.17					

84.69	81.29
48.82	49.21
138.13	128.57
162.91	162.86
165.41	159.36
76.29	79.91
97.10	99.35
55.84	57.74
55.26	54.03
106.63	111.51
62.86	58.24
139.74	149.98
82.59	86.11
69.86	81.63
174.96	167.00
213.96	201.54
102.68	106.16
77.61	76.91
161.96	162.16
178.46	177.78
27.63	28.88
16.58	19.03
33.55	35.88
48.00	49.65
29.70	29.88
43.45	44.28
57.38	59.75
36.43	36.33
47.90	49.40
21.28	24.93
42.25	43.38
28.95	32.08
23.13	21.08
20.95	22.43
19.78	20.33
30.00	29.98
32.70	37.93
38.85	42.08
17.43	19.83
39.03	40.78
17.03	17.85
25.45	22.00
38.08	38.35
15.98	17.98
40.70	41.15
25.90	24.53
28.73	29.35
42.55	43.70
58.95	59.70
47.95	50.58
50.83	52.73
45.73	46.85
41.45	40.95

14:16:36

```
.04005     .00055     .13387     .18292      .15677     .07709
.07915     .06804     .20961     .20485      .10754
.03424     .18510     .00000  176.73590   1   1   1   14
.04077     .00177     .13373     .18503      .15967     .07840
.07935     .06847     .21095     .20654      .10805
.03447     .18530     .00000  176.72950   2   1   1   14
.04155     .00301     .13370     .18709      .16245     .07971
.07965     .06897     .21230     .20821      .10863
.03479     .18568     .00000  176.72380   3   1   1   14
.04225     .00412     .13385     .18896      .16501     .08092
.07993     .06944     .21353     .20975      .10915
.03514     .18588     .00000  176.71870   4   1   1   14
.04266     .00490     .13391     .19044      .16710     .08179
.07994     .06963     .21442     .21089      .10939
.03519     .18573     .00000  176.71380   5   1   1   14
.04301     .00562     .13408     .19177      .16901     .08255
.07993     .06978     .21523     .21193      .10960
.
.
.

OPT. POLICIES FOR A 17 YEAR OLD PLANTER AND A 24 YEAR OLD TRACTOR ARE:

 POLICY:  8   RENT PLANTER 2
 EXPECTED UTILITY VALUE:       .1764877000E+03
 POLICY:  8   RENT PLANTER 2
 EXPECTED UTILITY VALUE:       .1769176000E+03
 POLICY:  8   RENT PLANTER 2
 EXPECTED UTILITY VALUE:       .1766433000E+03
 POLICY:  8   RENT PLANTER 2
 EXPECTED UTILITY VALUE:       .1769064000E+03
 POLICY:  8   RENT PLANTER 2
 EXPECTED UTILITY VALUE:       .1770494000E+03
 POLICY:  8   RENT PLANTER 2
 EXPECTED UTILITY VALUE:       .1770789000E+03
 POLICY:  8   RENT PLANTER 2
 EXPECTED UTILITY VALUE:       .1775914000E+03
 07:22:11
```

Appendix I

MODIFICATIONS TO THE FORTRAN CODE FOR CERES-MAIZE

This Appendix contains the modifications to the FORTRAN source code for CERES-MAIZE, Ver. 2.1s that account for the effects of surface crop residues on corn growth and yield. Chapter 4 and Appendix C explain why these changes were made. Appendix C also indicates which modifications were contributed by Frederic Dadoun[1].

Changes in the Main Program

The only change made to the main program for CERES-MAIZE was to insert a call statement for the new MULCHE subroutine. This occurs directly after daily weather data are read and before subroutine SOLT is called to estimate soil temperatures. Also, the call statement for the SOLT subroutine is no longer conditional on whether the option to calculate nitrogen balances is selected. Hence the statement:

```
IF (ISWNIT .NE. 0) CALL SOLT
```

is replaced by:

```
call mulche
call solt
```

Changes in Subroutine IPNIT

After subroutine IPNIT reads crop residue data from input file, FILE4, the following code is added:

```
c**** This portion allows you to partition the residues
c If depth is 0-1 all residues are at the surface
c If depth is greater than or equal to 20 (MB plow+secondary tillage)
```

[1] Ph.D candidate, Crop and Soils Department, Michigan State University.

```
c       all residues are incorporated
c If depth is less than 20 (Chisel plow+secondary tillage)
c       30 % of residue cover = 7% of biomass stays at the surface.
c If depth is less than 10 (Disk plow)
c       70 % of residue cover = 33% of biomass stays at the surface.

        if (sdep .le. 1.) then
          imulch = straw
          straw = 0.0
        elseif (sdep .le. 10) then
          imulch = 0.7 * straw
          straw = straw - imulch
        elseif (sdep .lt. 20) then
          imulch = 0.3 * straw
          straw = straw - imulch
        else
          imulch = 0.0
        endif
```

Two small changes are made in the section that checks to see whether crop residue data are within the proper range. These are preceded by comment lines with a small "c". The statement "GOTO 350" terminates consideration of crop residues and moves to the section of the IPNIT subroutine that reads fertilizer application data.

```
C *** While any parameter has negative value do : ********
  300    IF (STRAW .GT. 0. .AND. SDEP .GE. 0. .AND.
     &       SCN .GT. 0. .AND. ROOT .GT. 0) GOTO 350
c *** One line is added to read data for mulch **********
         if (straw .eq. 0. .and. sdep .eq. 0.) goto 350
            WRITE(*,1100) FILE4
            READ (5,'(A1)') ANS

            IF (ANS .EQ. 'E' .OR. ANS .EQ. 'e') THEN
               CALL MENU4
            ELSE IF (ANS .EQ. 'D' .OR. ANS .EQ. 'd') THEN

               IF (STRAW .LE. 0.) THEN
                  STRAW = 800.
               ENDIF
c *** The next statement is changed from .LE. to .Lt.
               IF (SDEP .Lt. 0.) THEN
                  SDEP = 30.
               ENDIF
```

Changes to Subroutine POTEV

The calculation of albedo and potential soil evaporation were changed in subroutine POTEV. Changes are printed in small letters.

```
      SUBROUTINE POTEV(EOS)

      Real*4 mulchalb,Ec,Em,mulchcov,cancov

      TD = 0.60*TEMPMX+0.40*TEMPMN
c
c  Coverage of the soil
c
      mulchcov=1-exp(-.32*mulch/1000)
      cancov=1-exp(-.75*lai)
c
c calculation of albedo
c
      mulchalb = 0.3
      IF (ISTAGE .LE. 6) THEN
         IF (ISTAGE .GE. 5) THEN
           ALBEDO=0.23+(LAI-4)**2/160
         ELSE
           albedo=cancov*0.23+mulchcov*(1-cancov)*mulchalb+
     & (1-mulchcov)*(1-cancov)*salb
         END IF
       ELSE
         albedo=(1-mulchcov)*salb+mulchcov*mulchalb
       END IF
c
c calculation of potential soil evaporation
c
      EEQ = SOLRAD*(4.88E-3 - 4.37E-3*ALBEDO)*(TD+29.0)
      IF ((TEMPMX .GE. 5.0) .AND. (TEMPMX .LE. 35.0)) THEN
         EO = EEQ*1.1
      ELSE IF (TEMPMX .GT. 35.0) THEN
         EO = EEQ*((TEMPMX-35.0)*0.05+1.1)
      ELSE
         EO = EEQ*0.01*EXP(0.18*(TEMPMX+20.0))
      ENDIF
c
c  Reducing factor due to canopy
c
      IF (LAI .LE. 1.0) THEN
         Ec = (1.-0.43*LAI)
      ELSE
         Ec = EXP(-0.4*LAI)/1.1
      ENDIF
c
c  Reducing factor due to mulch
c
      Em = exp(-0.22*mulch/1000)
```

```
c
c  Real soil evaporation
c
      Eos = Ec*Em*Eo

      RETURN
      END
```

Changes to Subroutine NTRANS

After the NTRANS subroutine partitions fertilizer applications to various soil layers and calculates urea hydrolysis, the following code is added to bring in organic matter from decomposed crop residue:

```
c **** fertilization due to mulch ***********************************
c when water infiltrates, all the decomposed mulch goes in the first
c pool of fresh organic matter in the first layer
         if (MFERTI .gt. 0.0) then
           fpool(1,1) = fpool(1,1) + mferti
           mferti = 0.0
         endif
```

Changes to Subroutine SOLT

The calculation of the moving average temperature in the first (top) soil layer was changed and statements for writing soil temperature to an output file were added to subroutine SOLT. Changes are printed in small letters.

```
      SUBROUTINE SOLT

      real*4 mulchcov

      if (doy .eq. isim) then
        open (12,file='solt.out',status='unknown')
      SUMSTT = 0
        write (12,120)
 120    format ('  DOY   TEMPM   TMA(1)   STG    ST(1)   ST(2)   ST(3)
     +  SUMSTT   MULCHCOV')
      endif

      XI = DOY
```

```
      ALX = (XI - HDAY) * 0.0174
      ATOT = ATOT - TMA(5)
      DO 100 K = 5,2,-1
         TMA(K) = TMA(K-1)
  100 CONTINUE
      mulchcov = 1 - exp(-3.5e-4*mulch)

      TMA(1) = (1.-ALBEDO-0.42*MULCHCOV) * (TEMPM + (TEMPMX-TEMPM) *
     &         SQRT(SOLRAD * .02)) + (ALBEDO+0.38*MULCHCOV) * TMA(1)

      ATOT = ATOT + TMA(1)
      AW = PESW
      IF (AW .LE. 0.0) AW = 0.01
      WC = AW / (WW * DEPMAX * 10.)
      F = EXP(B * ((1. - WC) / (1. + WC)) ** 2)
      DD = F * DP
      TA = TAV + AMP * COS(ALX) / 2.
      DT = ATOT / 5. - TA

      DO 200 L = 1, NLAYR
          ZD = -Z(L) / DD
          ST(L) = TAV + (AMP/2. * COS(ALX+ZD) + DT) * EXP(ZD)
  200 CONTINUE

      zdg = -2. / dd
      stg = tav + (amp/2. * cos(alx + zdg) + dt) * exp(zdg)

      stt = st(1) - 8
      if (stt .le. 0.0) stt = 0.0
      sumstt = sumstt + stt

      write (12,220) doy,tempm,tma(1),stg,st(1),st(2),st(3),sumstt,
     +                 mulchcov
  220 format (2x,i3,6(2x,f6.2),2x,f8.2,2x,f6.2)

      RETURN
      END
```

Changes to Subroutine PHENOL

The following changes were made in the calculation of daily thermal time in subroutine PHENOL.

```
c *** Modifications for Surface Mulch Effects Start Here
c STT = soil temperature degree days for early stages
c DTT = value used to calculate phenological stages
      if (istage .le. 2 .or. istage .ge. 7) then
       STT = ST(1) - TBASE
```

```
      endif
      if (stt. lt. 0.0) stt = 0.0
c *** Returning to original code


c ***** More Changes for Surface Mulch Effects
       if (istage .gt. 7) dtt = 0.5*dtt + 0.5*stt
       if (istage .lt. 3) dtt = 0.7*dtt + 0.3*stt
c ***** End of Changes for Surface Mulch Effects
```

Addition of Subroutine MULCHE

Subroutine MULCHE was developed by Frederic Dadoun and added to CERES-MAIZE. This subroutine was modified to incorporate surface crop residues during crop operations.

```
      SUBROUTINE MULCHE
C
C     ********** MULCH PARAMETERS ROUTINE ************************
C
C     Created by:  F. Dadoun,  April 1990
C
C     Called by:   MAIN

$Include:'maiz1.blk'
$Include:'maiz3.blk'
$Include:'maiz4.blk'
$Include:'resi.blk'
$Include:'ntrc1.blk'

      REAL*4 td,tedecf,uppermo,lowermo,enterseptmo,wadecf,pmulch
      REAL*4 MDECOMP

      open (13,file='mulch.out',status='unknown')
      IF (DOY.EQ.ISIM) THEN
         write (13,5)
5        format (' DOY    TD    RAIN   MULCH  MDECOMP MFERTI')
         MULCH = IMULCH
      ENDIF
C
C     TEMPERATURE FACTOR FOR DECOMPOSITION
C
      TD = 0.60*TEMPMX + 0.40*TEMPMN
      IF ((TD .GE. 0.) .AND. (TD .LE. 60.)) THEN
          IF (TD .GT. 35.) TEDECF=2.4-.04*TD
          IF ((TD.GE.20.) .AND. (TD.LE.35.)) TEDECF=1.0
          TEDECF=0.05*TD
      ELSE
```

```
            TEDECF=0.0
        ENDIF
C
C       MOISTURE FACTOR FOR DECOMPOSITION
C
        UPPERMO=LL(1)+0.3*(DUL(1)-LL(1))
        LOWERMO=LL(1)/2.0
        SLOPEMO=1.0/(UPPERMO-LOWERMO)
        ENTERSEPTMO=-SLOPEMO*LOWERMO
        IF ((SW(1).GE.LOWERMO) .AND. (SW(1).LT.UPPERMO)) THEN
            WADECF=SW(1)*SLOPEMO+ENTERSEPTMO
        ELSE
            IF (SW(1) .LT. LOWERMO) WADECF=0.0
            IF (SW(1) .GT. UPPERMO) WADECF=1.0
        ENDIF
C
C   MULCH DECOMPOSITION
C
        PMULCH=MULCH
        MULCH=MULCH*EXP(-.009*AMIN1(TEDECF,WADECF))
        IF (MULCH.LT.1.) MULCH=0.0
C
C   MULCH FERTILISATION
C
        IF (PRECIP .EQ. 0.0) THEN
         MDECOMP = MDECOMP + PMULCH - MULCH
         MFERTI = 0.0
        ELSE
C assume that rain is at the begining of the day
         MFERTI = MDECOMP
         MDECOMP = PMULCH - MULCH
        ENDIF

C   INCORPORATE 10% OF SURFACE RESIDUES WHEN PLANTING
        if (doy .eq. isow) then
            mulch = mulch * 0.9
            mferti = mferti + 0.1 * pmulch
        endif

C   INCORPORATE 10% MORE SURFACE RESIDUES WITH NH3 SIDEDRESS APPLICATION
        do 125 j=1,nfert
            if (doy .eq. fday(j) .and. iftype(j) .eq. 4) then
                 mulch = mulch * 0.9
                 mferti = mferti + 0.1 * pmulch
            endif
 125    continue

        WRITE(13,130) DOY,TD,precip,MULCH,MDECOMP,mferti
 130    FORMAT(I3,2x,f5.2,2x,f5.1,3(2x,f6.1))
        RETURN
        END
```

Changes to Subroutine GROSUB

The GROSUB subroutine was only modified by changing the radiation use efficiency parameter from 5.0 to 3.9 in the calculation of the PCARB variable. The modified calculation is:

```
PCARB = 3.9 * PAR / PLANTS * (1. - AMAX1(Y1,Y2))
```

Changes to Subroutine ROOTGR

The calculation of a root length density factor was changed in the ROOTGR subroutine by adding a soil temperature factor and making it an argument of the AMIN1 function.

```
c ****** Addition of Low Temperature Factor for Root Growth
       RTLTF = SIN(1.57 * (ST(L) - 8.) / (26. - 8.))
       RLDF(L) = AMIN1(SWDF,RNFAC,RTLTF)*WR(L)*DLAYR(L)
c ****** end of changes
```

RESI.BLK for CERES-MAIZE

The following block was included in the modified CERES-MAIZE subroutines to pass residue information between them.

```
c ****** RESI.BLK used for CERES-MAIZE ******

c common block for the information about residues
c
      real    imulch,mferti,mulch
      common/resi/imulch,mferti,mulch,mulchcov
```

Appendix J

MODIFICATIONS TO THE FORTRAN CODE FOR SOYGRO

This Appendix contains the modifications to the FORTRAN source code for SOYGRO, Ver. 5.42 that account for the effects of surface crop residues on soybean growth and yield. Chapter 4 and Appendix C explain why these changes were made.

Changes in Subroutine IPCROP

Subroutine IPCROP reads a long file of crop parameters, named CROPPARM.SBO. Surface residue weights were added at the end of the CROPPARM.SBO file and a statement was added to the end of subroutine IPCROP to read these data. The added statement is:

```
READ (10,*) (RESIDU(II),II = 1,5).
```

Changes in Subroutine IPSOIL

Code from the CERES-MAIZE subroutine SOILNI which initializes soil temperature calculations was inserted in SOYGRO subroutine IPSOIL. The soil temperature initialization was inserted immediately following the calculation of runoff from precipitation. The inserted code follows:

```
C     INITIALIZE SOIL TEMPERATURE INFORMATION
C
            ABD = TBD / (FLOAT(NLAYR))
            FST = ABD / (ABD + 686. * EXP(-5.63*ABD))
            DP = 1000. + 2500. * FST
            WW = .356 - .144 * ABD
            B = ALOG(500. / DP)
            ALBEDO = SALB
            SUMSTT = 0
            IF (TAV .LE. 0.) TAV = 20.
            IF (AMP .LE. 0.) AMP = 10.
```

Changes in Subroutine WATBAL

Three major changes are made to subroutine WATBAL. First, a CALL statement to subroutine MULCHS is inserted between the calculation of soil water contents after drainage and the calculation of potential soil evaporation. Second, the calculation of potential soil evaporation was modified to account for the effect of surface residue. Finally, in the calculation of root length, a soil temperature factor was added to the calculation of the root length density factor, RLDF(L), for each soil layer, L.

The CALL statement for subroutine MULCHS and the modified potential evaporation routine follow:

```
C-----------------------------------------------------------------------
C     MAJOR CHANGES FOR TILLAGE SYSTEM EFFECTS START HERE
C       Subroutine MULCHS determines mulch decomposition, mulch
C     cover, and soil temperature.
C-----------------------------------------------------------------------
      CALL MULCHS
C------------------------------------------------------------------------
C
C     ********* POTENTIAL EVAPORATION ROUTINE ***********
C
C------------------------------------------------------------------------
      TD = 0.60*TMAX+0.40*TMIN
      MULCHCOV = 1-EXP(-.32*RESDU/1000)
      CANCOV = 1-EXP(-.75*XHLAI)
      MULCHALB = 0.3
      IF (XHLAI .LE. 0.0001) THEN
                ALBEDO = (1-MULCHCOV)*SALB + MULCHCOV*MULCHALB
      ELSE
                ALBEDO = CANCOV*0.23 + MULCHCOV*(1-CANCOV)*MULCHALB +
     +               (1-MULCHCOV)*(1-CANCOV)*SALB
      END IF

C Calculation of potential soil evaporation
      EEQ = SLANG*(2.04E-4-1.83E-4*ALBEDO)*(TD+29.)
      EO = EEQ*1.1
      IF (TMAX .GT. 34.) EO = EEQ*((TMAX-34.)*0.05+1.1)
      IF (TMAX .LT. 5.0) EO = EEQ*0.01*EXP(0.18*(TMAX+20.))

C Reducing factor due to canopy
      IF (XHLAI .LE. 1.0) THEN
```

```
        EC = (1.-0.43*XHLAI)
      ELSE
        EC = EXP(-0.4*XHLAI)/1.1
      END IF

C Reducing factor due to mulch
      EM = EXP(-0.22*RESDU/1000)

C Real soil evaporation
      EOS = EC * EM * EO
C *** End of First Section of Changes for Surface Mulch Effects
```

The changes to the root length density calculation are:

```
c *** More Changes for Surface Mulch Effects ***********
c old version  RLDF(L) = SWDF*WR(L)*DLAYR(L)

           rltfac = sin(1.57 * (st(1) - tphmin) / (toptl - tphmin))
           rldf(L) = aminl(swdf,rltfac)*wr(L)*dlayr(L)

c **** End of Changes for Surface Mulch Effects ********
```

Changes to Subroutine GPHEN

The calculation of thermal time for the vegetative growth stages (less than or equal to NVEG1) was changed to a weighted average of thermal time based on air temperature and thermal time based on soil temperature. Variable DTT is thermal time based on air temperature, and already was calculated in Version 5.42. After DTT is calculated and before the cumulative sums of physiological days and photoperiod accumulator are calculated, the following code was inserted:

```
c  ***** Changes to Introduce Soil Temperature Effects Start Here *****

      if (n .le. nvegl) then
        stt = st(1) - tphmin
          dtt = 0.7*dtt + 0.3*stt
        dtx = dtt / (toptl-tphmin)
      endif

c  ****** Changes for Soil Temperature Effects End Here ***************
```

Changes to Subroutine CROP

Additional code to initialize soil temperature was added to subroutine CROP after the initialization of variables for a new run and before the WATBAL subroutine is called. Also, the treatment dimension was removed from the RESIDU(NTRT) variable. The modified code follows:

```
c *** Modifications for Surface Mulch Effects Start Here *****
C *** Determine Residue amount for the Treatment Selected ****

      resdu = residu(ntrt)

C *** Initialize soil temperature routine from SOILNI in CERES-MAIZE

            IF (XLAT .LT. 0.) THEN
            HDAY = 20.
            ELSE
            HDAY = 200.
            ENDIF

        TEMPM = (TMAX + TMIN) / 2.0
        DO 80 I = 1,5
            TMA(I) = TEMPM
 80     CONTINUE
        DO 90 L = 1,15
            ST(L) = TEMPM
 90     CONTINUE
        ATOT = TMA(1) * 5

*** End of Modifications for Surface Mulch Effects ****
```

Changes to Subroutine PHOTO

Two changes were made to subroutine PHOTO. First, the temperature factor used to calculate the effect of temperature on the photosynthesis rate was changed to a weighted average of air and soil temperature during vegetative growth stages. This variable is called TDAY. Second, the calculation of the temperature effect was given a cubic functional form, as is explained in Appendix C. The modified code follows:

```
c  **** Change for soil temperature effect *****

      if (n .le. nvegl) tday = 0.7*tday + 0.3*st(1)

c  ***** end of change for soil temperature effect *****

      TDAYSQ = TDAY*TDAY
      TDAYCU = TDAYSQ*TDAY
      TPHFAC = (XPHOT(1)*TDAY+XPHOT(2)*TDAYSQ+XPHOT(3)*TDAYCU)/YPHOTM
      IF (TDAY .LE. 7.) TPHFAC = 0.0

c **** End of Changes to PHOTO ****
```

Changes to Subroutine VEGGR

Subroutine VEGGR also was modified to consider the effect of soil temperature on root growth. This modification occurs in the calculation of variable RFAC2.

```
C-----------------------------------------------------------------------
C     CALCULATE ROOT DEPTH RATE OF INCREASE, CM/DEGREE DAY (RFAC2)
C-----------------------------------------------------------------------
      RFAC2 = TABEX(YRTFAC,XRTFAC,VSTAGE,4)

c ***** Modification for Soil Temperature Effect ***************

        rltfac = sin(1.57*(st(1)-tphmin)/(toptl-tphmin))
        rfac2 = rfac2 * rltfac

c ***** End of Soil Temperature Effect Changes *****************
```

Addition of Subroutine MULCHS

The MULCHE subroutine used in CERES-MAIZE was modified for use in SOYGRO by adding soil temperature calculations and writing to a soil temperature output file.

```
$STORAGE:2

      SUBROUTINE MULCHS
C
C     ********** MULCH PARAMETERS ROUTINE ************************
C
```

```
C     Created by:  F. Dadoun      Modified for SOYGRO by Mark Krause
C                  April 1990                              March 1992
C
C     Called by:   WATBAL
C
$Include: 'COMGRO.DAT'
$Include: 'COMSOI.DAT'
$Include: 'resi.blk'

      REAL*4 td,tedecf,uppermo,lowermo,enterseptmo,wadecf,mulchcov
C     TEMPERATURE FACTOR FOR DECOMPOSITION

      TD = 0.60*TMAX + 0.40*TMIN
      IF ((TD .GE. 0.) .AND. (TD .LE. 60.)) THEN
          IF (TD .GT. 35.) TEDECF=2.4-.04*TD
          IF ((TD.GE.20.) .AND. (TD.LE.35.)) TEDECF=1.0
          TEDECF=0.05*TD
      ELSE
          TEDECF=0.0
      ENDIF
C
C     MOISTURE FACTOR FOR DECOMPOSITION
C
      UPPERMO=LL(1)+0.3*(DUL(1)-LL(1))
      LOWERMO=LL(1)/2.0
      SLOPEMO=1.0/(UPPERMO-LOWERMO)
      ENTERSEPTMO=-SLOPEMO*LOWERMO
      IF ((SW(1).GE.LOWERMO) .AND. (SW(1).LT.UPPERMO)) THEN
          WADECF=SW(1)*SLOPEMO+ENTERSEPTMO
      ELSE
          IF (SW(1) .LT. LOWERMO) WADECF=0.0
          IF (SW(1) .GT. UPPERMO) WADECF=1.0
      ENDIF
C
C  MULCH DECOMPOSITION
C
      RESDU=RESDU*EXP(-.009*AMIN1(TEDECF,WADECF))
      IF (RESDU.LT.1.) RESDU=0.0
      IF (JUL .EQ. IPLT) RESDU = RESDU * 0.9

C      PART OF SUBROUTINE SOLT IN CERES-MAIZE
C               AS MODIFIED BY DADOUN AND KRAUSE
C
C *** Subroutine to calculate daily average soil temperature at the
C     center of each soil layer.
C
C     Changed 20 Aug 1990, F. Dadoun      Modified March 1992, M. Krause
C
      TEMPM = (TMAX + TMIN) / 2.0
      XI = JUL
      ALX = (XI - HDAY) * 0.0174
      ATOT = ATOT - TMA(5)
```

```
      DO 300 K = 5,2,-1
         TMA(K) = TMA(K-1)
  300 CONTINUE
      mulchcov = 1 - exp(-3.5e-4*RESDU)

      TMA(1) = (1.-ALBEDO-0.42*MULCHCOV) * (TEMPM + (TMAX-TEMPM) *
     &         SQRT(SRAD * .02)) + (ALBEDO+0.38*MULCHCOV) * TMA(1)

      ATOT = ATOT + TMA(1)
      AW = PESW
      IF (AW .LE. 0.0) AW = 0.01
      WC = AW / (WW * DEPMAX * 10.)
      FST = EXP(B * ((1. - WC) / (1. + WC)) ** 2)
      DD = FST * DP
      TA = TAV + AMP * COS(ALX) / 2.
      DT = ATOT / 5. - TA

      DO 400 L = 1, NLAYR
          ZD = -Z(L) / DD
          ST(L) = TAV + (AMP/2. * COS(ALX+ZD) + DT) * EXP(ZD)
  400 CONTINUE

      stt = st(1) - 7
      if (stt .le. 0.0) stt = 0.0
      sumstt = sumstt + stt

      write (48,220) jul,tempm,tma(1),st(1),st(2),st(3),sumstt,mulchcov
 220  format (2x,i3,5(2x,f6.2),2x,f8.2,2x,f6.2)

      RETURN
      END
```

RESI.BLK for SOYGRO

The following block was included in the modified SOYGRO subroutines in SOYGRO to pass residue information between them.

```
c common block for the information about residues
c
      common/resi/ residu(4),resdu
      common/solt/ z(15),hday,tav,amp,ww,b,dp,albedo,tma(6),st(15),atot
```

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