

OPTIMAL AGRICULTURAL MANAGEMENT DECISIONS
FOR CONTROLLING NONPOINT SUB-SURFACE
CHEMICAL CONTAMINATION

By

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1984

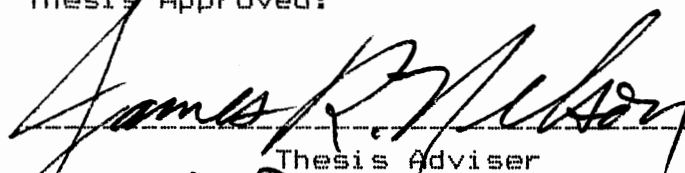
Master of Science
Oklahoma State University
Stillwater, Oklahoma
1986


Submitted to the Faculty of the
Graduate College of the
Oklahoma State University
in partial fulfillment of
the requirements for
the Degree of
DOCTOR OF PHILOSOPHY
December, 1989

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Thesis Approved:


Thesis Adviser








Dean of the Graduate College

PREFACE

The research contained herein addressed the relationship of between agricultural management decisions (pesticide selection, tillage practices and irrigation), subsurface chemical leaching and agricultural producers net returns. The procedures involved a synthesis of stochastic dynamic programming and computer simulation. The impacts of various management practices on chemical leaching and crop yields were demonstrated using the Environmental Protection Agency's Pesticide Root Zone Model and the Agricultural Research Service's Erosion Productivity Index Calculator, respectively.

The data obtained from these simulations were incorporated into a risk neutral stochastic dynamic programming model to facilitate the examination of optimal management practices for various levels of chemical leaching. Selection of optimal practices were based on the maximum present value of net returns subject to various standards on leaching.

The practices with the largest impact on leaching are, in order of significance, irrigation, chemical selection and tillage practices. The management practices which result in the highest leaching levels are also those practices which result in the highest present value of net returns (eg. water

intensive irrigation schemes). Consequently, the imposition of standards on leaching can result in substantially reduced present value of expected net returns over the planning horizon.

The author would like to extend his deepest appreciation to several people who have provided assistance during the course of this research and my entire degree program. First, my appreciation goes to the Department of Agricultural Economics for providing a favorable environment for which to conduct this research. Also, the financial support provided by Dr. Norman N. Durham and the OSU Center for Water Research is greatly appreciated.

The comments and suggestions of Dr. Daniel J. Bernardo, Dr. David Pyles and Dr. William McTernan helped to substantially improve the dissertation. Also, Dr. Abelardo Rodriguez helped the author grasp the subtleties of dynamic optimization at an early and crucial stage in the research. Most importantly, I am very grateful for, among other items, the guidance and encouragement that my advisor Dr. James Nelson provided, not only in my dissertation research, but throughout my graduate program here at OSU. I am particularly appreciative of the confidence that Dr. Nelson showed in me during my research. On more than one occasion he allowed me to resolve potentially prohibitive difficulties when many others would not have.

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CHAPTER I

INTRODUCTION

Introduction to the Problem of Agricultural Pollution

Ground water is an important resource in the United States with regard to both consumption and production. In 1985 withdrawals of ground water totaled approximately 78 billion gallons per day. This quantity is over twice the quantity of ground water used in 1950. Estimates are that approximately 50 percent of the total U.S. population relies on ground water for consumption, and in rural areas this figure may approach 97 percent (U. S. Environmental Protection Agency, 1987a). Water consumed by livestock is 55 percent ground water, and irrigated agriculture, the largest single consumer of ground water, used almost two-thirds of the total 1985 withdrawals (Solley, Chase and Mann).

The nation's ground water resources were, until recently, thought to be at low risk for contamination due to geological, agronomic and chemical factors. Consequently, agricultural chemicals were applied with minimal consideration for the possibilities of ground water contamination. It became evident that this position needed to be re-evaluated in 1979 when ground waters in California

and New York were found to be contaminated with dibromochloropropane (DBCP) and Temik. In September of 1983 the Environmental Protection Agency suspended all soil use of ethylene dibromide (EDB) after finding the chemical in ground water in California, Florida, Georgia and Hawaii. Shortly after these findings, a report by the U.S. Office of Technology Assessment identified agriculture as a prominent source of ground water contamination (U.S. Congress). Since that time interest in ground water quality has been fueled by a number of ground water contamination occurrences. Today, it is estimated that more than 100,000 of the nation's 13,000,000 drinking water wells have detectable pesticide concentrations (U.S. Environmental Protection Agency, 1987b); at least 19 different agricultural chemicals originating from nonpoint sources have been detected in ground water in 24 states (see Table I) (U.S. Environmental Protection Agency, 1987a); and Nielsen and Lee estimate that over 50 million people rely on ground water which is potentially contaminated from nutrients and/or chemicals.

The precipitates of ground water contamination include significant health implications and monetary costs. Abilities to detect chemicals at very low concentrations in ground water have improved greatly in recent years, however abilities to predict the risks associated with exposure to various levels of chemical concentration have not increased substantially. However, examples of documented adverse health effects from exposure to contaminated drinking water

TABLE I
PESTICIDE CONTAMINATION OCCURRENCES

Pesticide	Use*	State	Typical Positive ppb**
Alachlor	H	MD, IA, NE, PA, MN	0.1-10
Aldicarb (sulfoxide & sulfone)	I, N	AR, AZ, CA, FL, MA, ME, NC, NJ, NY, OR, RI, TX VA, WA, WI	1-50
Atrazine	H	PA, IA, NE, WI, MD, MN	0.3-3
Bromacil	H	FL	300
Carbofuran	I, N	NY, WI, MD	1-50
Cyanazine	H	IA, PA, MN	0.1-1.0
DBCP	N	AZ, CA, HI, MD SC	0.02-20
DCPA (and acid products)	H	NY	50-700
Dicamba	H	IA, MN	0.1-2
1,2 Di- chloropropane	N	CA, MD, NY, WA	1-50
Dinoseb	H	NY	1-5
EDB	N	CA, FL, GA, SC WA, AZ, MA, CT	0.05-20
Fonofos	I	IA	0.1
Metolachlor	H	IA, PA, MN	0.1-0.4
Metribuzin	H	IA	1.0-4.3
Oxamyl	I, N	NY, RI	5-65
Propachlor	H	MN	0.2-0.5
Symazine	H	CA, PA, MD, MN	0.2-3.0
1,2,3 Tri- chloropropane	N	CA, HI	0.1-5.0

Source: U.S. Environmental Agency, 1987a.

*H=herbicide; I=insecticide; N=nematicide

**ppb = parts per billion; 1 ppb = 1/1000 ppm; 1 ppm = 1 mg/l

do exist and include cancer, genetic mutations, reproductive disorders and central nervous system disorders (U.S. Environmental Protection Agency, 1985; Hoar et al; Life Systems, Inc.).

With regard to monetary costs, the primary item is avoidance costs - i.e., the costs of avoiding exposure to contaminated ground water. Nielson and Lee estimate that preventative monitoring costs required for the nation's households would range from \$0.9 to \$2.2 billion. Other preventative measures could include purchasing home water treatment units or alternative sources of drinking water. The costs associated with these measures would vary depending on the particular contamination case. The potential exists for cleaning or containing contaminated aquifers; however, these activities are very expensive and feasible only for isolated occurrences. Additional costs to society could include lower agricultural productivity resulting in lower farm incomes, increased health costs due to increased illness, loss in national productivity due to health and illness, and of course, environmental damage.

The focus on agriculture as a polluting industry has generated significant activity in the policy and legislative arenas. The primary legislation designed to address agricultural pollution of ground water resources consists of The Water Quality Act of 1987; The Federal Insecticide, Fungicide and Rodenticide Act (FIFRA) and The Safe Drinking Water Act. The Water Quality Act of 1987 required each state to appropriate funds for addressing nonpoint pollution

problems. In addition to providing technical assistance, education and training for producers, states must correct existing problems by implementing management practices that control agricultural runoff.

FIFRA enables the Environmental Protection Agency to control the use of a pesticide if the chemical endangers either the environment or the population. This control includes suspensions and bans on the use of hazardous chemicals. FIFRA was the legislation used to ban the nematocide DBCP after it was found in water wells in California and other states. This contamination occurred in spite of the fact that recommended application rates were followed.

The Safe Drinking Water Act encourages states to develop plans to prevent chemicals and bacteria from contaminating public ground water wells. The objective of the Act is to expand control over previously uncontrolled sources of contamination such as agricultural chemicals and animal wastes. It should be noted that there are currently two additional legislative amendments under consideration, and the potential exists for the SDWA to be modified as well (Batie).

The Physical Process of Pesticide Leaching

Agricultural pollution problems can be categorized as point source and nonpoint source pollution. Point source pollution is defined as those occurrences which can be attributed to one specific source. Nonpoint sources are diffused

occurrences which cannot be linked to any one particular source and are generally associated with very large geographic areas and possibly large numbers of sources. Within the two primary classifications there are six subgroups: surface or subsurface pollution and nutrient, sediment and pesticide pollution. The primary focus for this research is nonpoint, subsurface, pesticide pollution.

There are three primary components of chemical loss from agricultural production activities which pose environmental hazards: runoff, erosion and leaching. Runoff loss occurs when water (irrigation and/or precipitation) is applied following chemical application which results in the chemical literally being transported by water runoff. Runoff loss is rather unique in that it is primarily a timing question, i.e. producers should avoid irrigating immediately after chemical applications or applying chemicals immediately prior to rainfall and/or irrigation. Additional chemical loss occurs when the chemical attaches itself to soil particles and is lost when soil erosion occurs. This ability or propensity of the chemical to attach itself to soil is determined primarily by the soil/chemical specific organic matter partition coefficient. That is, some chemicals possess a higher propensity to attach themselves to soil than others. Moreover, soils with low organic matter content retard adsorption.

Both runoff loss and erosion loss are surface problems. To some extent washoff and erosion loss can be controlled by surface practices such as Soil Conservation Service (SCS)

Best Management Practices (BMPs) which are designed to reduce erosion. By design, BMPs reduce erosion loss by increasing surface water retention and hence increase the infiltration rate of water into the subsurface. By increasing the retention and infiltration rate the surface water runoff is reduced, consequently reducing the rate of soil loss. However, the increased rate of infiltration can increase the rate of leaching of chemicals. Crowder and Young (1987) recognized this inverse relationship for nutrients. For a complete discussion of additional adverse implications of conservation tillage practices see Hinkle; and Baker and Laflen. Of course the infiltration will be exacerbated by supplementing precipitation with irrigation water.

The consequences of surface management practices on subsurface leaching of chemicals are determined to some degree by the water solubility of the chemical. Given increased surface retention and increased infiltration, if the chemical of interest is highly water soluble, (i.e. has the propensity to dissolve in water rather than be adsorbed by organic matter), then the possibilities of increasing chemical leaching are enhanced. This statement is true to the extent that water solubility impacts the distribution of the chemical between soil and water. As a result of this potential inverse relationship between surface and subsurface concerns a paradox presents itself to policy makers and producers. Efforts to control surface, agricultural, nonpoint pollution problems may in fact increase the possibilities of subsurface nonpoint pollution. The challenge

facing policy makers then, is to form environmental policy which is consistent with the multi-dimensional nature of the general problem of agricultural, nonpoint pollution. This paradox takes on additional importance due to the fact that many conservation tillage practices are not being implemented on the most highly erodible lands (Hinkle).

Another important characteristic of the subsurface chemical leaching problem which is relevant to policy makers is the dynamic, intertemporal nature of subsurface pollution, particularly with regard to ground water resources. Chemical applications, depending on the exact physical characteristics of the chemical and the chemical's relationship with the soil, can have a cumulative effect on the environment. Consequently, policy formulation must consider the dynamic nature of chemical leaching and the fact that the policy imposed may affect many future periods (Miranowski).

The Management Approach to Controlling Agricultural Nonpoint Pollution

The problem of agricultural pollution provides an interesting and complex problem for policy makers, producers and society as a whole. Proposed means of controlling agricultural pollution are of the "performance, institution, behavior" type (Schmid). Producers are induced, through institutional regulations or incentives, to adopt management practices consistent with environmental concerns. An example of this type of policy design is the Soil Conservation Service's system of BMPs designed to reduce erosion loss of

productive topsoil. In this program, soil conserving management practices are subsidized to encourage producers to adopt such practices. BMP's include management practices such as reduced and no-till tillage practices, contouring and terracing.

The design of an appropriate institutional system is essential in achieving the social and environmental goals associated with the nonpoint agricultural pollution problem. Sharp and Bromley state that "the major hurdle [in controlling agricultural pollution] is not technology, rather it is the design of institutional arrangements to encourage the incorporation of this technology into ongoing farming systems." Sharp and Bromley continue to say "The institutional arrangements for effecting a program of this nature must have the capacity to (a) generate relevant information with respect to performance, (b) adapt over time to changing conditions, and (c) reconcile the often conflicting incentives of other programs which may dampen the incentives for pollution abatement".

A variety of instruments for adopting practices consistent with environmental protection could result from future legislation. These incentives include: 1) positive or negative incentives on the use of production inputs, 2) mandatory soil conservation management practices, 3) bans on hazardous chemicals, 4) regulations on land use and chemical applications on particular types of land and 5) mandatory management practices for applying chemicals (Crowder, Ribaudo and Young).

Review of Economic Literature Addressing Agricultural, Nonpoint Pollution

The literature addressing agricultural, nonpoint pollution is dominated by research dealing with surface nutrient problems, while fewer deal with subsurface nutrient problems. Even fewer studies address subsurface chemical loadings.

Horner analyzed alternative policies to achieve a nitrogen pollution standard in subsurface return flows in the San Joaquin Valley of California. The policies compared were an effluent charge on nitrogen, water treatment and a no-nitrogen control. Incomes, production and costs were compared for each control using a multiperiod linear programming model. Results were consistent with the Baumol and Oates proposition of least cost control by utilizing emitter charges. Crop which required less nitrogen became more desirable. Agricultural production with the effluent charge was less than the production under the return-flow treatment alternative.

Jacobs and Timmons used a combination of a linear programming, cost-minimization model and incremental cost-benefit analysis to address the problem of sediment and phosphorus losses to streams from crop and pasture land. The objectives were to estimate the least-cost means of achieving particular quality levels via agricultural production practices and to estimate the benefits necessary to offset the costs associated with pollution reduction. The

min cost
v.t. pro

alternative production practices consisted of combinations of crop rotations; minimum tillage or conventional tillage; and contouring or terraces. Alternative production practices were capable of reducing soil and phosphorus pollution, however costs to producers are substantial. Also, considerable reuse of the water and large recreational benefits are required to justify the pollution reductions on an economic basis.

Crowder and Young (1987) investigated the tradeoffs between the costs of soil conservation practices and water quality and discussed the economic implications of such tradeoffs. The authors utilized the Chemicals, Runoff, and Erosion from Agricultural Management Systems (CREAMS) model to assess pollutant losses from agricultural cropland to surface and ground water. Of several different conservation tillage practices, no-till planting, reduced tillage and sod waterway systems were found to be most cost effective in controlling soil and nutrient runoff losses. Other results include: 1) subsurface leaching of nutrients is slightly increased by soil conservation practices; 2) terracing and permanent vegetative cover impose the greatest societal costs for water quality protection; and 3) public cost sharing and // tax incentives would be required for adoption of the more expensive practices. Crowder and Young recommended that efforts be taken to encourage the adoption of cost-effective water protection practices for critical acreage. Moreover, in intensively farmed areas, extensive treatment of land is necessary for agricultural best management practices to

significantly improve water quality.

Diebel, et al. examined the potential effectiveness of policies for reducing nitrate contamination of ground water from agriculture. Linking the CREAMS model with a mixed integer programming model, the potential effects of various ground water protection policies were examined. The policies analyzed are cost-sharing of construction costs for manure storage facilities, fertilizer combined with cost-sharing of manure storage facility construction and a ban on commercial nitrogen purchases. The study indicates that cost-sharing and nutrient management education would result in substantial reduction (potentially 40 percent) in dairy related nitrate loadings. Cost sharing was shown to induce producers to construct manure storage facilities which reduce nitrate loading with minimal losses in incomes. It was noted that greater reductions in loading could be achieved through mandatory policies such as taxes and fertilizer bans than with voluntary cost-sharing. However, due to the disapproval of the public, these policies were recognized as perhaps being infeasible.

A stochastic programming model similar to that proposed by Charnes and Cooper was developed by Milon to evaluate the economic implications of reliability criteria and multiple effluent controls on nonpoint source pollution. An integrated watershed model -- Pesticide Root Zone Model (PRZM) -- was used to generate probability distributions for chemical, nutrient and sediment loadings. A three dimensional aquifer model was used to track loadings into and

throughout the aquifer. The author was concerned with both surface and subsurface problems and nutrient as well as pesticide leaching. Results indicate that reliability requirements significantly increase the cost of satisfying control objectives. Also, the importance of realizing unintended implications for control variables other than the variable of interest was stressed. This multi-objective aspect is similar to the paradox presented by erosion and leaching.

Anderson, et al. proposed a model for determining on-site standards for Temik applications on potatoes that satisfy Long Island drinking water standards. A contamination function was postulated which mapped field applications to ground water concentrations. Concentration was treated as a stock variable and profits were maximized in a constrained utility maximization problem (i.e. the stock of pollution could not exceed the maximum contaminant level (MCL)). Stressed in the research was the need for data and field testing for pesticides, particularly regarding pest mortality. Efforts by Anderson, et al. to link Temik applications and net returns were prevented by insufficient data with regard to application rates and pest mortality.

Much attention has been devoted to the development of theory with which to explain and describe the optimal policy instruments for controlling stochastic environmental externalities (Baumol and Oates; Weitzman 1974 and 1978; Adar and Griffin; and Kwerel). Two additional works, by Griffen and Bromley; and Shortle and Dunn, are of particular interest

and will be discussed now.

Griffin and Bromley were the first to differentiate in any formal manner between point and nonpoint source externalities. Using the theoretical base developed by Baumol and Oates, Griffin and Bromley extended the analysis to include a nonpoint source externality. Using the implicit function theorem, it was shown that the production of the externality is expressible as a continuously differentiable function of all inputs and outputs. Analyzed by Griffin and Bromley were nonpoint incentives, least cost systems of standards, individual management incentives for each production activity affecting emissions and standards as the dual to the management incentives.

For the nonpoint incentives and the least cost standards the individual determinants of emissions are monitored as opposed to the emissions themselves. The actual emissions are then calculated by the nonpoint production function. For each firm the incentives will be different since the derivatives of the nonpoint production function will be evaluated at different levels. Each incentive is a marginal charge or subsidy.

Each of the policy alternatives proposed by Griffin and Bromley induces the allocatively efficient achievement of the target objective. The different instruments vary with regard to data requirements. To obtain the least cost goal in two of these programs, the nonpoint incentives and nonpoint standards, individual farmers must have information on the nonpoint production functions. If this information is not

available, one of the other two programs may be desirable. Moreover, additional differences between programs are transactions costs, equity and rate of adoption. Griffin and Bromely also stress the need for work on the externality production function. Also noted is that though least cost efficiency is achieved with standards these standards are different for each farm. Thus, when regulations are equivalent across farms (or across subsets of farms) incentive programs rather than standards are more efficient.

Shortle and Dunn contributed to the theory of nonpoint source externalities by addressing stochastic production of the externality and assuming an informational differential similar to that assumed by Adar and Griffin, in favor of the firm. Therefore, the agency cannot predict with certainty what reaction they would provoke from firms with any particular policy instrument. The relative efficiencies of four policy instruments were analyzed: 1) management practice incentives 2) management practice standards 3) estimated runoff incentives and 4) estimated runoff standards.

Excluding transactions costs, the principle result is that an appropriately specified management practice incentive should generally outperform estimated runoff standards, runoff incentives and management practice standards. It is noted that the important factor is the quality and not quantity of information conveyed to managers. None of the instruments, however, will provide an efficient solution when there are multiple sources and/or risk aversion on the part of the firms.

The literature discussed above represents the research to date which deals with the general problem of nonpoint, agricultural pollution. The research directed at subsurface chemical leaching is limited. The two works which focused on pesticides, Milon and Anderson et al., are limited in that they are static and the decisions available to the producer are limited primarily to BMPs. Consequently, there appears to be a need for research which addresses the paradox of surface/subsurface environmental concerns while incorporating the dynamic nature of subsurface pesticide contamination. Additionally, the research should increase the alternatives producers have to maximize returns while satisfying environmental objectives.

Problem Statement

Caddo county, Oklahoma is a predominately agricultural county in southwestern Oklahoma (see figure 1). The combination of the area's agronomic and geologic characteristics in addition to the significant agricultural production occurring in the area provide an interesting and relevant research problem on agricultural, nonpoint subsurface pollution.

The soils in the area are sandy (approximately 67 percent sand for Pulaski soils) hence water infiltration is substantial. Most significantly, the Rush Springs aquifer which underlies much of Caddo county has depths to water below the soil surface of 0 to 150 feet (Oklahoma Water Resources Board). The aquifer is a fine-grained, cross-

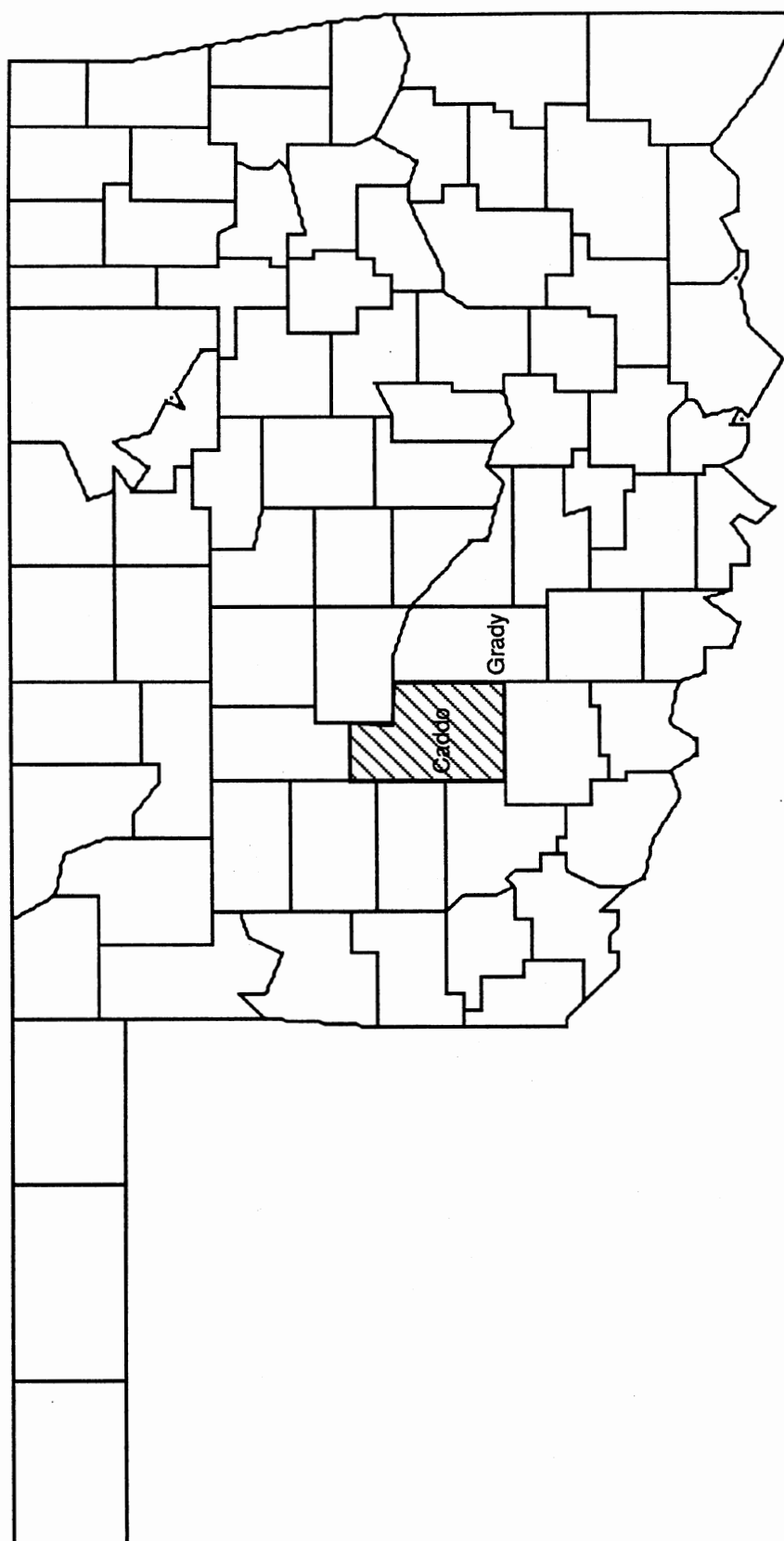


Figure 1. Caddo County, Oklahoma Study Area

bedded sandstone aquifer and ranges in thickness from 200 to 330 feet. The wells in the aquifer yield a maximum of 1,000 gallons per minute and average about 400 gallons per minute. The Rush Springs aquifer provides good quality water to the area for domestic, municipal, irrigation and industrial use.

The sandy soils present in Caddo county are advantageous to the production of peanuts; consequently, Caddo county is the top peanut producing county in Oklahoma. In 1987, 32,650 acres of peanuts were planted in Caddo county of which 31,715 acres were irrigated, primarily with sprinkler irrigation. This peanut acreage is more than twice that of Bryan county, the second highest producing county, with 15,950 irrigated and 5,000 dryland acres (1987 Oklahoma Agricultural Statistics).

Two important production pests for Caddo county peanut producers are fungi and nematodes (Kirby; Sholar; and Jackson). Two examples are Sclerotinia fungus and Root Knot nematodes. Chemicals used to combat these pests include Botran and Rovral for Schlerotinia and Temik, Furadan and Nemacur for Root Knot. Given the environmental characteristics of the county and the chemical applications required for peanut production there exists a real potential for ground water contamination.

According to a 6 year study by personnel in the OSU Plant Pathology department, use of the fungicide Rovral to combat Sclerotinia results in approximately a 2 to 4 percent better peanut yield than does the use of Botran (Jackson). An 11 year study also suggests that use of Temik or Nemacur to

combat Root Knot result in approximately 7.1 and 4 percent, respectively, smaller peanut yields than does use of Furadan (Jackson). It must be stressed that these figures are highly dependent upon the pest of interest.

Of interest here is not only the relative effectiveness of the chemicals in controlling pests but also their propensities to leach into the subsurface. Rovral is marginally more prone to leaching than Botran, Nematicur is much less likely to leach than either Temik or Furadan. It should also be noted that both Rovral and Botran are significantly smaller leachers than Temik, Furadan or Nematicur. As a result of these findings, the tradeoff between net returns and concern for ground water quality looms as a significant and pressing issue for the study area.

Objectives

The primary objective of this study was to examine, for Caddo county, Oklahoma peanut producers, the optimal decision rules for irrigation management, tillage practices and pesticide selection for alternative ground water protection scenarios. More specifically, the objectives are as follows:

- 1) to identify a feasible set of possible management plans for Caddo county, Oklahoma peanut producers including irrigation management schemes, tillage practices and chemical selection decisions.
- 2) to estimate the economic costs and returns associated with each management plan.
- 3) to demonstrate the relationship between each possible management plan and chemical leaching below the peanut root zone.

- 4) to determine the relationship between each management plan and peanut yields.
- 5) to incorporate chemical leaching and peanut yield data into a stochastic dynamic programming (DP) model to determine optimal decision rules for irrigation, tillage and chemical decisions. An optimal decision rule is that rule which maximizes the per hectare net present value of returns over a planning horizon subject to environmental standards.

Summary of Procedures

The procedures followed to achieve the above stated objectives include a synthesis of microcomputer simulation and dynamic optimization. Various management plans were examined for optimality subject to specified root zone leaching standards.

Feasible production plans were identified based on information obtained from professional agriculturalists familiar with the Caddo county study area. Special consideration was given to factors which contribute to the possibilities of chemical leaching: i.e. chemical selection, irrigation and tillage decisions. Cost and price information was obtained from agricultural statistics for the area and from the O.S.U. Enterprise Budgets.

A micro-computer simulation model was used to demonstrate the relationship between the respective management plans and chemical leaching. The model was calibrated for the area using area weather data, soil properties and management practices typical for the area.

The relationships between the management plans and peanut yields were determined using a micro-computer plant growth

model. This model was also adapted to the area using local weather data, soil data and management practices typical for the area.

The data generated with the two simulation models were then incorporated into a stochastic DP algorithm. This model, written in Fortran, runs on a microcomputer and facilitates the determination of optimal management plans.

Outline

Chapter II includes a review of dynamic programming theory and literature. In Chapter III the management plans are presented and the simulation models and the DP algorithm used are discussed. A discussion of the stochastic elements of the DP algorithm is also provided. Results and implications are presented in Chapter IV. The research is summarized in Chapter V and comments regarding conclusions and additional research are presented.

CHAPTER II

REVIEW OF DYNAMIC PROGRAMMING

Dynamic Programming Theory

The term dynamic programming was first used by Bellman in 1957 to define an approach to solving multi-stage decision problems. The decision problems are set over a planning horizon which is divided into equal and discrete intervals termed stages. In any stage, the condition or state of the system is completely described by the magnitudes of the state variables. The state variables are transformed from stage to stage by decisions made in each stage. Though a continuous form of DP does exist, DP problems are typically discrete.

Though the original DP formulation was for multi-stage or multi-decision problems, the approach is equally as valid for single decision problems as well, i.e. only one decision is made in each stage. It should be noted, however, that though only one decision variable is selected this decision may in fact entail a number of variables. This is exemplified by the decision variables in this research. For the problem presented herein, the number of decisions or controls available to the manager is 18. Yet each of these 18 controls consists of a selection of a tillage practice, an irrigation method and a pesticide selection. The problem

then becomes one of maximizing a function influenced by the above controls. The control which maximizes the function is termed the optimal control.

Wagner describes the structure of the dynamic programming algorithm as follows:

- i) The decision variables with their associated constraints are grouped according to stages, and the stages are considered sequentially.
- ii) The only information about previous stages relevant to selecting optimal values for the current decision variables is summarized by a so-called state variable, which may be n -dimensional.
- iii) The current decision, given the present state of the system, has a forecastable influence on the state at the next stage.
- iv) The optimality of the current decision is judged in terms of its forecasted economic impact on the present stage and on all subsequent stages.

A policy is any decision making rule which yields an allowable sequence of decisions. The policy which maximizes a preassigned function of the state variables is termed the optimal policy.

Consider the generalized form of the DP objective function.

$$(24) \quad \text{Max} \sum (R_{ij}(u_j, x_t))$$

where

R_{ij} = the reward associated with going from
state i to state j
 u_j = the j th control
 x_t = the state of the system in stage.

Equation (24) indicates that the sum of the stage rewards are being maximized over the planning horizon. The rewards, R_{ij} , are dependent upon the state of the system and the

control selected. Solution of equation (24) in the DP structure relies on the following principle from Bellman:

Principle of Optimality. An optimal policy has the property that whatever the initial state and initial decision are, the remaining decisions must constitute an optimal policy with regard to the state resulting from the first decision."

Two extensions of the basic DP algorithm are of interest. The first extension, discounting, provides a means of invoking a preference over present or future returns. That is, equation (24) will now be written:

$$(25) \quad \text{Max} \sum \{B^{t-1} * R_{1,j}(u_j, x_t)\}$$

where

$$B = (1/(1+i))$$

i = the discount rate.

Now the returns resulting in the future periods will be discounted by the interest rate.

The model represented in (24) and (25) is deterministic. That is, each relationship and outcome is known with certainty. Suppose however, that the controls which are available from which to select result in a distribution of values for the state variables rather than a single deterministic value. Now equation (25) will become

$$(26) \quad \text{MAX} \sum \{B^{t-1} * E(R_{1,j}(u_j, x_t))\}$$

where E is the expectations operator.

Associated with equation (26) is a state transformation function which maps the decision variables into state space. The transformation function takes the following deterministic form,

$$(27) \quad x_{n+1} = G(x_n, u_{n+1})$$

That is, the state of the system in stage $n+1$ is

determined by the state of the system in the prior period and the decision made in the current period.

In many decision problems, the state transformation may depend on the initial state, the control and random events which are not controlled by the decision maker. Provided that the random events affecting the state transformation in stage j occur in stage j and no earlier, the problem can be formulated as a stochastic DP problem. Hence equation (27) is rewritten as

$$(28) \quad x_{n+1} = G(x_n, u_{n+1}, e_t)$$

where e_t is an error term. Processes such as these are referred to as first order, Markov processes (Howard).

Notice that in the stochastic formulation projections for the state variable are only one stage into the future.

Typically, in DP applications, the state variables are discretized. The discrete state variables used in this research will be discussed later.

Review of Natural Resource and Agricultural Related Dynamic Programming Applications

As researchers' computer literacy and computational capabilities increase the use of numerical solution algorithms such as DP is increasing. See Taylor, 1989; Taylor, 1987; and Burt, 1982 for a thorough discussion of the adoption of DP.

The initial published work in the agricultural economics profession was by Burt and Allison (1963) only six years

after Richard Bellman's pioneering book on dynamic programming. In an effort to "indicate the importance of dynamic programming and the magnitude of its potential application in the realm of farm management decisions" Burt and Allison developed a Markovian dynamic programming problem in which the decision was to leave farm land fallow or plant wheat dependant upon the stochastic level of soil moisture in the field. Results indicated that the optimal policy based on the stochastic soil moisture at wheat planting time yielded expected returns exceeding those of continuous wheat and a policy of alternating wheat and fallow.

Since the original work by Burt and Allison, others have applied the DP algorithm to a variety of economic decision making problems. Works addressing environmental or natural resource questions include optimal ground water use (Burt 1964a), conjunctive use of ground water and surface water (Burt 1964b), ground water management and surface water development for irrigation (Burt 1967), natural resource management (Burt and Cummings, 1977), and soil conservation (Burt, 1981). Taylor and Burt (1984) developed near-optimal decision rules for controlling wild oats in spring wheat. Several studies have addressed irrigation managment using DP in some form (Bekure and Eidman, 1971; Yaron and Dinar 1982; Raju, Lee, Biere and Kanemasu, 1980).

Many financial and inventory management problems fit well into a DP framework. Mjelde, Garoian and Conner used stochastic DP to determine optimal hay inventories for range

cattle producers given uncertain forage production due to meteorological events. Garoian, Mjelde and Conner also determined optimal marketing strategies for calves and yearlings with uncertain forage production and prices. Rodriquez and Taylor used DP to test the certainty equivalence property for a yearling operation. Examples of modelling the decision process for federal programs such as the conservation reserve and commodity programs are also available (Allard, 1989; Duffy, 1989). Novak and Schnitkey used a stochastic DP model to determine the potential effects of stock investment outside of an agricultural enterprise on firm financial structure as well as the effects of the agricultural returns on optimal investment decisions. The performance of a variable amortization loan repayment plan for a hog finishing operation under differing loan repayment plans and loan levels was demonstrated by Schnitkey and Novak using stochastic DP.

CHAPTER III

MODEL DEVELOPMENT

The approach followed in this research is a systems analysis approach to environmental and economic modelling. A combination of computer simulation and stochastic dynamic programming was used. In this chapter the management plans and associated variable costs data are presented, then each of the models is discussed beginning with the simulation models.

Management Plans

Feasible management plans were identified by utilizing data and information from professional agriculturalists knowledgeable of Caddo county peanut production (Sholar; Jackson; Kirby). Two important pests for Caddo county peanut production -- Sclerotinia fungus and Root Knot nematodes -- were discussed in Chapter I. Also discussed were alternative chemicals producers can apply to aid in controlling these diseases.

Typically, peanut production in Caddo County is performed using traditional tillage practices. There is however, the possibility of no-till peanut production in Caddo county. No-till peanuts are planted directly into wheat stubble. The relevant implications are less soil erosion, greater water

infiltration, lower machinery costs and the manager must switch from preplant and preemergence herbicide applications to preemergence and postemergence applications (Sholar). Herbicide costs are increased slightly with the no-till practices due to higher prices of the postemergence herbicides. As discussed in Chapter I, no-till production could increase the potential for chemical leaching into the subsurface. The components of the respective tillage methods are provided in Table II.

Given the sandy soils in the area, furrow irrigation, which is the most inexpensive of the viable irrigation techniques, results in low application efficiency due to significant infiltration. Consequently, sprinkler irrigation is the most common irrigation technique in the area. Two variations on sprinkler irrigation are examined in this research. Traditionally, producers apply irrigation water at a flat rate. For this research a rate of 7.62 centimeters (3 inches) every 10 days was applied. On days when precipitation occurs, irrigation water is applied up to but not exceeding the 7.62 centimeters.

A more sophisticated approach examined in this research involves soil monitoring to determine the rate of irrigation application resulting in greatly reduced gross applications, hence reduced irrigation variable costs, more efficient applications and reduced infiltration relative to the traditional flat rate application. The monitoring process involves measuring the soil moisture in the first three

TABLE II
TILLAGE COMPONENTS

Conventional Tillage	No-Till
Field Cultivator	Fertilizer Spreader
Disk (3) ¹	Planter
Fertilizer Spreader	Row Cultivator (2) ¹
Planter	Peanut Digger
Row Cultivator (2) ¹	Peanut Harvester
Peanut Digger	Sprayer
Peanut Harvester	
Sprayer	

¹() denotes times over

centimeters of the soil surface and applying water once the soil moisture falls to 1.5 times the wilting point. Water is applied until the soil in the top 3 centimeters is returned to field capacity.

Given the above information, alternative production plans typical for the area can be formulated. The manager will make decisions with respect to: 1) the irrigation method, 2) which chemical to use for the respective pests and 3) conventional tillage or no-till production practices. The controls used in this study are provided in Table III. It should be emphasized, that the problem environment represents ideal conditions for both peanut production and chemical leaching. The very sandy soil present in Caddo county which is ideal for peanut production also increases the potential for pesticide leaching. Furthermore, spatial variation in soil characteristics or other conditions could alter both the economic and environmental results.

Cost and Price Information

Cost and returns information for alternative production activities are essential to optimal decision making, hence the need to determine the variable costs for the respective management plans. This objective was achieved by utilizing information from the OSU Enterprise Budgets. The primary cost differences between the different plans are chemical, irrigation, and machinery costs. A peanut price of \$0.27 per pound is used. The discount rate is 10 percent. The

TABLE III
ALTERNATIVE MANAGEMENT PLANS ANALYZED

control	irrigation	chemical	tillage
1	dryland	Furadan	conventional
2	"	"	no-till
3	limited	"	conventional
4	"	"	no-till
5	traditional	"	conventional
6	"	"	no-till
7	dryland	Nemacur	conventional
8	"	"	no-till
9	limited	"	conventional
10	"	"	no-till
11	traditional	"	conventional
12	"	"	no-till
13	dryland	Temik	conventional
14	"	"	no-till
15	limited	"	conventional
16	"	"	no-till
17	traditional	"	conventional
18	"	"	no-till

expected peanut yield for each management plan was included in the DP algorithm.

Irrigation variable costs were obtained from Dale, et al. for a natural gas fueled, side-roll irrigation system with \$3.5/mcf fuel costs and 150 foot pump lift. The per acre inch variable cost for a side-roll irrigation system under these conditions is \$2.83. The irrigation efficiency is 70 percent. The variable production costs per hectare associated with each production item are provided in Table IV. The total per hectare variable costs for the management plans are provided in Table V.

Peanut Plant Growth Simulations

The Erosion Productivity Impact Calculator (EPIC) (U.S. Department of Agriculture, 1988b) was used to demonstrate the relationship between the management plans and peanut yields. EPIC is a mathematical model developed specifically for application to the erosion-productivity problem. Specific components of EPIC include weather simulation, hydrology, erosion-sedimentation, nutrient cycling, plant growth, tillage, soil temperature, economics and plant environmental control. In addition to the erosion-productivity problem, EPIC is a useful decision-making model to examine optimal management decisions involving drainage, irrigation, water yield, erosion control management decisions involving drainage, irrigation, water yield, erosion control (both wind and water), weather, fertilizer and lime applications, pest

TABLE IV
DOLLARS PER HECTARE VARIABLE
PRODUCTION COSTS

	Conventional Till	No-Till

machinery:		
field cultivator	12.36	
disk (3) ¹	59.61	
spreader	7.66	7.66
row planter	20.00	20.00
row cultivator (2) ¹	27.04	27.04
peanut digger	20.00	20.00
peanut harvester	25.00	25.00
sprayer	13.60	13.60

irrigation:		
limited	20.53	20.53
traditional	140.12	140.12
other:		
foliar disease		
control	123.00	123.00
herbicides	46.76	62.95
fertilizer	49.41	49.41
seed	175.00	175.00
gypsum	18.53	18.53
hoeing labor	14.82	14.82

Study Chemicals		
Furadan	112.29	112.29
Nemacur	145.14	145.14
Temik	155.37	155.37

¹() indicates times over

TABLE V
TOTAL DOLLARS PER HECTARE VARIABLE COSTS
FOR THE RESPECTIVE MANAGEMENT PLANS

	Conventional Tillage	No-Till
Furadan:		
Limited	745.61	689.83
Traditional	865.20	809.42
Dryland	725.08	669.30
Nemacur:		
Limited	778.46	722.68
Traditional	898.05	842.27
Dryland	757.93	702.15
Temik:		
Limited	788.69	732.91
Traditional	908.28	852.50
Dryland	768.16	712.38

control, planting dates, tillage and crop residue management.

EPIC has been tested at more than 150 locations in the continental U.S. and 13 locations in Hawaii. Results from the testing indicate that EPIC is capable of simulating erosion, crop growth and related processes realistically (Williams, et al.). EPIC is micro computer compatible, is written in FORTRAN and contains a main program and 83 subprograms or about 4450 FORTRAN statements. EPIC is a management oriented model which allows great flexibility in describing the production environment for a crop. Yields can be simulated with EPIC in a continuous fashion such that yield distributions can be obtained. These continuous simulations encompass intertemporal variables such as soil moisture, residue and erosion. EPIC also allows the user to approximate different pest effects through the adjustment of parameters in the model. Inputs into EPIC include meteorological data, tillage practices, cropping information and soil properties which allow the user to parameterize the simulations to specific problem situations.

Chemical Leaching Simulations

The Pesticide Root Zone Model (PRZM) (U.S. Environmental Protection Agency) was utilized to demonstrate the relationship between the management plans and pesticide leaching rates. PRZM simulates the vertical movement of chemicals in the unsaturated zone within the root zone and extending to the water table. The model consists of

hydrology and chemical transport components that simulate runoff, erosion, plant uptake, leaching, decay, foliar washoff and volatilization.

Output can be obtained for a variety of variables on a daily, monthly or annual basis. PRZM allows the dynamic simulation of the transport of potentially toxic chemicals, particularly pesticides applied to soil or foliage. These dynamic simulations allow the consideration of peak loads, the prediction of peak events, and the estimation of time-varying mass emissions or concentration profiles.

Like EPIC, PRZM uses relatively accessible data and runs on a micro computer. PRZM has performed favorably in limited performance testing in New York, Wisconsin, Florida and Georgia. Daniels, Milon and Mize are additional studies using PRZM. Villeneuve et al., discuss the significant implications for the performance of PRZM of uncertainty surrounding key parameters including chemical degradation rates and adsorption constants.

Leaching below the root zone and root zone storage rates measured in kilograms per hectare were calculated using PRZM. The peanut root zone used is 120 centimeters (48 inches). The need for simulating storage rates is discussed later. PRZM is a management model which incorporates soil properties, tillage practices, cropping information, chemical properties, and meteorological data. These data are consistent or identical to the data used in the EPIC model.

The Dynamic Programming Model

To determine optimal decision rules for irrigation, tillage and pesticide selection the data from EPIC and PRZM as well as cost and returns information were incorporated into a stochastic, dynamic program. Equation (26) can be rewritten in a recursive form,

$$(28) \quad V_n(RZSTR^N, RZSTR^F, RZSTR^T) = \max_U \{ YLD^k * P_p - VC^k + B * V_{n-1}() \}$$

where

- B = the discount factor
- YLD^k = the expected peanut yield with the k^{th} control, u_k
- P_p = the peanut price
- VC^k = the per hectare variable production cost for the k^{th} control, u_k
- U = a vector of controls
- RZSTR = the kilograms per hectare root zone storage for Nematicur (N), Furadan (F) and Temik (T).
- n = the number of stages remaining in the planning horizon.

Equation (28) is solved numerically for an optimal decision policy subject to

$$(29) \quad RZSTR_{n-1}^N = F(RZSTR_n^N, u_k, e_t);$$

$$(30) \quad RZSTR_{n-1}^F = G(RZSTR_n^F, u_k, e_t);$$

$$(31) \quad RZSTR_{n-1}^T = H(RZSTR_n^T, u_k, e_t).$$

$$V_0 = 0.0.$$

Where e_t is a random error term and u_k is the control selected.

From the objective function it can be seen that discounted, expected net returns are maximized over a planning horizon. The firm objective of maximizing expected

net returns is consistent with risk neutrality. Moreover, the rewards R are maximized subject to the control selected in the current stage and the state of the system in the current period.

The State Variables

Chemical leaching below the root zone and chemical storage in the root zone are stochastic due primarily to meteorological events. To incorporate the stochastic nature of leaching and storage the Hyperbolic Tangent CDF Approximation Technique (TANH) is applied to the data generated with the PRZM models (Taylor, 1981; Taylor, 1984). The TANH technique provides a relatively straightforward means of estimating empirical cumulative distribution functions for observed data. Application of the TANH method yields transitional probabilities for ten discrete storage levels for the respective chemicals given one of the ten possible storage levels as an initial state and a control selection. For Furadan, root zone storage ranges from 0.049311 to 0.1030111 kilograms per hectare; NemaCur storage ranges from 0.0015748 to 0.0047651 kg/ha; and Temik storage ranges from 0.0002111 to 0.062022 kg/ha.

The following ordinary least squares equations were used to characterize the PRZM model output by relating root zone storage to past storage values and the controls. Standard errors are in parenthesis.

$$(32) \quad RZSTR^N_t = 0.00540449 + 0.09961041 * RZSTR^N_{t-1} \\ (0.00020286) \quad (0.03596991)$$

$$- 0.00011757 \cdot \text{TDUM} - 0.00002456 \cdot \text{WATER} + e_t$$

(0.00004172) (0.00000101)

$$R^2 = .902$$

$$(33) \quad \text{RZSTR}^F_t = 0.11146913 + 0.11246295 \cdot \text{RZSTR}^F_{t-1}$$

(0.00469113) (0.0393337)

$$- 0.00439926 \cdot \text{TDUM} - 0.00042159 \cdot \text{WATER} + e_t$$

(0.00081703) (0.00001957)

$$R^2 = .886$$

$$(34) \quad \text{RZSTR}^T_t = 0.06973066 - 0.12281762 \cdot \text{RZSTR}^T_{t-1}$$

(0.00269211) (0.04101655)

$$+ 0.0031472 \cdot \text{TDUM} - 0.00054395 \cdot \text{WATER} + e_t$$

(0.00115163) (0.00002347)

$$R^2 = .818$$

where

RZSTR = root zone storage for the respective pesticide

TDUM = 1,0 dummy for conventional tillage, no-till, tillage practices

WATER = average annual total water available for the respective irrigation and dryland methods

e_t = error term.

The coefficient of determination for each of the equations are acceptable. Moreover, each of the regressors in equations (32)-(34) are significant at the .995 percent significance level. Differences in coefficient signs across chemicals can be attributed to pesticide specific characteristics which cause the chemicals to interact differently with a specific soil, water, tillage practice and existing level of storage.

Using the TANH method the empirical cumulative distribution functions for the error terms, e_t , are estimated with the following equations:

$$(35) \quad F_N(e_t) = .5 + .5 \cdot \text{TANH}(-0.02037989 + 0.8181218 \cdot e_t)$$

(0.07307787) (0.05794736)

$$(36) \quad F^r(e_t) = .5 + .5 * \text{TANH} \left(\frac{-0.04858701 + 0.8975313 * e_t}{(0.07463893) \quad (0.06314235)} \right)$$

$$(37) \quad F^T(e_t) = .5 + .5 * \text{TANH} \left(\frac{-0.02077822 + 0.8744615 * e_t}{(0.07500425) \quad (0.06118196)} \right)$$

The coefficients of equations (34) - (36) are maximum likelihood estimates. These functions are then incorporated into the DP algorithm to be used in calculating transitional probabilities.

The Policy Variable

Though root zone storage is the state variable of interest with regard to environmental concerns, storage is not the primary variable of interest with regard to environmental pollution and policy. The primary interest is the quantity of chemical which leaches beyond the root zone into the subsurface. State variables in DP problems are typically of the stock type; for example the quantity of range forage crop, quantity of water in a reservoir or stock of a resource. Leaching unfortunately does not fit into this category; it is more of a flow concept. Consequently, it was necessary to identify an acceptable stock type variable which was closely related to leaching to facilitate the calculation of leaching. Root zone storage was selected as this variable.

Moreover, for the problem to be modelled in a dynamic framework, it is necessary to have a variable which links the stages together. Root zone storage does this as indicated in equations (32) and (33). Therefore, once the state variable

RZSTR is calculated, the rate of change of RZSTR is calculated for the respective chemicals: $\Delta = \text{RZSTR}_t - \text{RZSTR}_{t-1}$. Δ is then weighted by the inverse of the application rate for the specific chemical to obtain the regressor RATIO . RATIO is then used to calculate the quantity of leaching associated with each initial level of root zone storage and control selected for each pesticide. Formally,

$$\text{LCH}^k_t = G(\text{RATIO}_t, u_t).$$

The following ordinary least squares equations were estimated.

$$(40) \quad \text{LCH}^F_t = -0.06214638 * \text{TDUM} + 0.00118847 * \text{WATER} \\ (0.00893901) \quad (0.00006737)$$

$$-17.5521446 * \text{RATIO} + e_t \\ (12.32281273)$$

$$R^2 = .723$$

$$(41) \quad \text{LCH}^N_t = -0.0211151 * \text{TDUM} + 0.00049416 * \text{WATER} \\ (0.00385276) \quad (0.00002898)$$

$$-85.31842112 * \text{RATIO} + e_t \\ (40.37312184)$$

$$R^2 = .724$$

$$(42) \quad \text{LCH}^T_t = -0.2169619 * \text{TDUM} + 0.01597257 * \text{WATER} \\ (0.11849427) \quad (0.00089566)$$

$$-301.652 * \text{RATIO} + e_t \\ (76.16513082)$$

$$R^2 = .799$$

where

TDUM and WATER are as defined before.

The coefficient of determination for equations (40)-(42) are acceptable. Each of the regressors except RATIO for

Furadan and Nematicur and TDUM for Temik are significant at the .9995 percent significance level. Again, WATER plays a significant role in determining the level of leaching.

The Environmental Standards

The environmental standards analyzed in this research are based on the premise that standards are essentially constraints on using specific production practices which violate the constraints. This premise underlies many articles including Shortel and Dunn and Griffin and Bromely. Also, an effort is made through the standard specification to consider relative toxicity of a nematicide. These standards discriminate against the more toxic Temik and Carbofuran by imposing stricter standards. The three different environmental protection scenarios are as follows:

- i) no traditional irrigation of any of the three nematicides; $N=0.03$, $C=0.07$, and $T=1.77$ kilograms per hectare.
- ii) no traditional irrigation of Furadan and no no-till practices with traditional irrigation when using Nematicur, no traditional irrigation when using Temik; $N=0.04$, $F=0.07$ and $T=1.77$ kilograms per hectare.
- iii) no traditional irrigation in conjunction with no-till practices for either Furadan, Nematicur or Temik; $N=0.04$, $F=0.095$ and $T=1.77$ kilograms per hectare.

These standards limit the use of the specified practices even at the lowest initial states. Moreover, they can and often do limit other practices in higher initial states.

A comment is in order regarding the relationship of the

policy variable, root zone leaching, and ground water contamination. The quantity of chemical leaching beyond the root zone provides an estimate of the total mass introduced into the subsurface environment. Considering the shallow depths to ground water for the Rush Springs aquifer in Caddo county, (0 to 150 feet), the possibility of ground water contamination from root zone leaching is significant.

It is important to realize, however, that as the chemical is transported downward through the subsurface, decay and distribution will continue. However, the rates of decay and distribution at depths greater than the root zone can and will vary greatly from the rates at more shallow soil depths. Moreover, the aerobic decomposition of the chemical is replaced by anaerobic decomposition of which there exist minimal information. There is reason to believe that the rate of decay decreases as the chemical travels deeper into the subsurface.

The Control Variables

The controls in the dynamic program are the management plans identified in Table III. Stated formally,

$$u_j = [w_r, cn_i, cs_q]$$

$$j=1, \dots, 18; \quad r=1, 2, 3; \quad i=1, 2; \quad q=1, 2$$

where

u_j = the j^{th} control
 w_1 = dryland farming
 w_2 = limited irrigation
 w_3 = traditional irrigation
 cn_1 = conventional tillage
 cn_2 = no-till

cs₁ = Furadan
cs₂ = Nematicur
cs₃ = Temik

The Policy Iteration Method proposed by Howard is used as a means of numerically solving for controls which maximize equation (28). The Policy Iteration Method consists of two steps: the value-determination operation and the policy-improvement routine. Simply stated, equation (28) is solved for each control using the respective expectations and returns. Then, for each possible combination of states, the control which maximizes (28) is selected by comparing each control with alternative controls.

Data

Meteorological Data

The PRZM model requires daily values for precipitation, pan evaporation and mean temperature. Precipitation is read in centimeters, mean temperature is read in degrees Celsius and pan evaporation is read in centimeters. Meteorological data for this study were obtained from Chickasha, Oklahoma. Chickasha is in Grady county which adjoins the study area.

The EPIC model utilizes the same 25 year Chickasha weather series of maximum temperature, minimum temperature and precipitation. Temperatures are in degrees Celsius while precipitation is in millimeters. The meteorological record for both PRZM and EPIC is January 1, 1954 to December 31, 1978.

Soil and Chemical Data

Important aspects of the chemical leaching problem are the characteristics of the soil onto which the chemical is applied, and the specific properties of the applied chemical. The single soil used in this analysis is Pulaski, a very sandy soil ideal for peanut production. The Pulaski soil characteristics taken from Soil Survey Investigative Reports (USDA-SCS, 1966) are presented in Table VI. The relevant properties of the study chemicals, taken from the USDA-ARS Interim Pesticide Properties Database, Version 1, are provided in Table VII.

Irrigation Data

Two irrigation methods were analyzed. The first is a traditional approach of applying a flat rate (7.62 cm) every 10 days beginning July 1 and ending September 15. On irrigation days where precipitation occurs the 7.62 cm is the upper bound.

The second irrigation method examined is a limited irrigation scheme. The method is designed primarily to maintain the natural soil moisture, as opposed to increasing the soil moisture, and to minimize chemical leaching. The method entails soil moisture monitoring and application of water when the soil moisture reaches 1.5 times the wilting point. Irrigation water is then applied to return the top three centimeters of the soil to field capacity. This method begins applying water on June 1 and ends September 1.

TABLE VI
 IMPORTANT SOIL CHARACTERISTICS:
 PULASKI SOIL¹

horizon	1	2	3	4	5	6	7
depth (cm)	10	15	23	54	86	126	166
bulk							
density (t/m ³)	1.4	1.4	1.4	1.5	1.5	1.55	1.6
wilting							
point (t/m ³)	.108	.108	.108	.121	.121	.122	.125
field							
capacity	.267	.267	.267	.249	.249	.233	.204
sand %	68.5	68.5	68.5	44.8	44.8	39.5	28.2
silt %	20.8	20.8	20.8	38.9	38.9	43.0	51.8
clay %	10.7	10.7	10.7	16.3	16.3	17.5	20.0
organic							
carbon %	0.39	0.39	0.39	0.21	0.21	0.18	0.69
crop							
residue	0.034	0.43	0.44	0.60	0.60	0.09	0.002

¹Values are mean values

TABLE VII
SELECT CHEMICAL CHARACTERISTICS

	Solubility (mg/l)	Half life (days)	Decay (/day)
Furadan	350	30	0.02284003
Nemacur	700	20	0.03406367
Temik	6000	30	0.02284003
Rovral	13	20	0.03406367
Botran	7	10	0.06696701

It should be emphasized that the irrigation methods used in this research, and the dryland production for that matter, are not purported to be economically or environmentally optimal. It is hoped that the irrigation techniques as well as the other management practices used, encompass the range of practices available. The impacts of variations from these extremes can possibly provide insights into intermediate adjustments in agricultural production practices.

CHAPTER IV

RESULTS

Each of the alternative management plans was simulated with the EPIC and PRZM micro computer models. Results of these simulations, in addition to cost and expected yield data, were used to determine optimal decisions for each root zone storage level and associated chemical leaching level. The TANH method was used to incorporate distribution functions for nematicide storage into the DP algorithm to represent the stochastic state variables. Results of each of the three modeling steps will be reported

Results from the PRZM simulations of the use of Rovral and Botran to control *Sclerotinia* fungus, prompted the efforts directed toward the dynamic modelling of the *Sclerotinia* example to be aborted. The intertemporal link between applications of either Rovral or Botran is minimal. Moreover, the PRZM simulations indicate that only very small quantities of either Rovral or Botran leach below the root zone and even in the worst case do not leach to the water table.

Results of the EPIC Simulations

The EPIC simulations for the respective controls generated the yields which provided the mean yields contained

in Table VIII. The base yields are those of the dryland, conventional tillage production plans. The increases in expected yields from changing to limited irrigation from dryland production are 11.1 and 10.1 percent for conventional tillage and no-till Nematicur, respectively. For Furadan, using limited irrigation results in yield increases of 11.8 and 10.6 percent for conventional and no-till, respectively. Hence, the expected yield increases are marginally larger with Furadan. Moreover, the yield increases are marginally larger for conventional tillage as opposed to no-till. In moving to a less sophisticated, more water intensive irrigation technique yield increases are 66.6 percent and 62.8 percent, respectively, for Nematicur, conventional till and no-till. These yields are 85.2 and 79.3 percent greater than the dryland yields. For Furadan, yield increases of 67.4 and 62.6 percent are experienced for conventional and no-till, respectively, using traditional versus limited irrigation; these yields are 87.1 and 80.0 percent higher than dryland yields. The Nematicur dryland yields are approximately 3 percent less than Furadan's for the conventional till scenarios and 3.3 percent less for the no-till scenario. Recall that an approximately 4.4 percent yield effect was incorporated into the EPIC simulations through the pest factor coefficient in the model to accommodate differences in effectiveness of the fungicide.

Nematicur yields for limited irrigation are approximately 3.6 and 4.1 percent less than Furadan's for conventional

TABLE VIII
SIMULATED PEANUT YIELDS FOR EACH
MANAGEMENT PLAN IN POUNDS
PER HECTARE

	Dryland	Irrigation	
		Limited	Traditional
Furadan:			
Conventional			
Tillage	4060.0	4540.0	7600.0
No-Till	4300.0	4760.0	7740.0
Nemacur:			
Conventional			
Tillage	3940.0	4380.0	7300.0
No-Till	4160.0	4580.0	7460.0
Temik:			
Conventional			
Tillage	3860.0	4300.0	7120.0
No-till	4060.0	4480.0	7260.0

tillage limited and traditionally irrigated scenarios. For the no-till Nematicur scenarios, yields are 3.3, 3.9 and 3.7 percent less than the no-till Furadan scenarios for dryland, limited irrigation and traditional irrigation, respectively. Using no-till production practices allows producers to increase organic matter and soil moisture, both of which are beneficial to crop production. The EPIC simulations support this hypothesis in that in each case the no-till yields are larger than the conventional yields.

For Furadan, the yield increase for using no-till production practices rather than conventional tillage are 5.9, 4.8 and 1.8 percent, respectively for dryland, limited irrigation and traditional irrigation scenarios. Observe that the increase declines as the quantity of irrigation water increases. As the quantity of irrigation water available increases the importance of soil water retention is diminished. For Nematicur the increases in yields are 5.5, 4.5 and 2.2 percent. Again the increases decline as irrigation is increased. Note that the Nematicur increases are in each case smaller than for Furadan.

Using Temik to combat Root Knot nematodes results in lower yields than either Nematicur or Furadan. An approximately 7.0 percent yield effect, relative to Furadan, was incorporated into the EPIC simulations to incorporate the effectiveness of Temik in controlling Root Knot nematodes. Reductions in yields relative to Furadan range from approximately 5.0 to 6.7 percent and approximately 1.8 to

2.75 percent relative to Nemacur. With Temik and conventional tillage, moving from dryland to limited and traditional irrigation results in increases of 11.4 and 84.4 percent, respectively. When using no-till, yield increases of 10.3 and 78.8 percent occur when by moving from dryland to limited or traditional irrigation. Increases due to no-till versus conventional tillage for dryland, limited and traditional irrigation are 5.2, 4.0 and 1.9 percent, respectively.

In summary, the traditional irrigated schemes result in the largest yields followed by the limited irrigation then dryland schemes. Yield increases due to using no-till practices decline as the rate of irrigation increases. Furadan use results in greater yields in all scenarios than does Nemacur, while use of Nemacur in all cases results in yields greater than Temik.

Results of the PRZM Simulations

The leaching levels measured in kilograms of ingredient per hectare from January 1 to December 31 are provided in Table IX. First note that in each case the levels of Temik leaching are greater than the levels for either Nemacur or Furadan. These differences range from 74.82 percent for the Nemacur conventional tillage, dryland to 7.62 percent for the Furadan, no-till, traditional irrigation plan.

For Nemacur, leaching is increased by 33.6, 30.4 and 81.2 percent for the dryland, limited irrigation and traditional

irrigation schemes, respectively by using no-till rather than conventional tillage. Increased leaching occurs by moving from dryland, conventional tillage to limited and traditional irrigation schemes, 10.1 and 235.93 percent, respectively. Increases with no-till practices are 7.6 and 355.55 percent, respectively.

When using Furadan, going from conventional tillage to no-till results in increases in leaching of 55.5, 74.4 and 69.3 percent for dryland, limited and traditional irrigation production, respectively. Moving from dryland to limited and traditional irrigation results in increases of 14.6 and 471.34 percent for conventional tillage and 28.57, and 783.08 percent for no-till production.

Temik leaching exceeds that of either Furadan or NemaCur by an order of magnitude. When using conventional tillage, Temik leaching increases by 5.2 and 72.4 percent by moving from dryland to limited and traditional irrigation, respectively. When no-till practices are being utilized moving from dryland to limited or traditional irrigation results in Temik leaching increases of 7.7 and 84.28 percent, respectively. No-till practices increase leaching by 13.3, 16.0 and 21.2 percent for dryland production, limited and traditional irrigation.

In summary, in each case the leaching rate of Temik is greater than that of NemaCur and Furadan. No-till production results in greater leaching rates than conventional tillage and this difference increases as

TABLE IX
AVERAGE KILOGRAMS PER HECTARE
LEACHING RATES FOR EACH
MANAGEMENT PLAN

	Dryland	Irrigation	
		Limited	Traditional
Furadan:			
Conventional			
Tillage	0.0171	0.0196	0.0977
No-Till	0.0266	0.0342	0.2349
Nemacur:			
Conventional			
Tillage	0.0128	0.0141	0.0430
No-Till	0.0171	0.0184	0.0779
Temik:			
Conventional			
Tillage	0.9705	1.0210	1.6733
No-till	1.0997	1.1845	2.0266

irrigation increases. These increases are of course greater for Temik. The increases in leaching due to irrigation are greatest for the traditional irrigation schemes and are largest for no-till production Furadan.

Results from the Dynamic Programming Algorithm

The EPIC and PRZM results discussed in the preceding sections were incorporated into the dynamic programming algorithm. The objective of the algorithm was to maximize the present value of the expected net returns subject to various standards for leaching. The particular environmental standard imposed upon producers has a significant effect on the controls selected and hence the returns from the production activities. The standards are discussed in Chapter III.

The first item to note regarding the results is that the optimal controls are invariant to the planning horizon stage and Temik state. Also, since yields are not effected by the level of pesticide storage the results can be reported with relative ease. The optimal controls for the respective initial states of Furadan and Nematicur and any initial Temik state under the first regulatory standard are provided in Table X. Recall from Chapter III that this regulatory standard restricted the upper bound on irrigation to the limited irrigation scheme. In the lowest Furadan initial state, and each Nematicur state, control 4 is optimal; this is

the Furadan, no-till limited irrigation control. In the first 2 Nematicur states, once control 4 violates the standard, control 10 becomes optimal. Control 10 represents the Nematicur, no-till, limited irrigation management plan. As the Nematicur initial state increases, however, producers are unable to satisfy the standard on Nematicur and must use the Furadan, no-till dryland or limited management plans (controls 2 and 3), depending on the specific Furadan state.

The present value of the expected net returns over the 5 year planning horizon are provided in Table XI. Recall that the peanut yields with limited irrigation are substantially lower than the yields from traditional irrigation. Consequently, restraints on using traditional irrigation results in greatly reduced net returns. Additionally, Furadan results in higher yields and lower per hectare costs than either Temik or Nematicur. Also, no-till practices result in greater yields and lower machinery costs than conventional tillage.

The highest present value is obtained by using control 4 -- \$2,483.00. As the initial state for Nematicur and Furadan increase, the standard becomes binding causing producers to switch to controls 2 and 3 resulting in a lower present value of net returns.

The controls in the higher states of Nematicur differ in tillage and irrigation practices. Consider controls 2 and 3. The dryland, no-till Furadan control (control 2) has a present value of \$2050.32 while the limited irrigation, no-

TABLE X
OPTIMAL CONTROLS FOR REGULATORY STANDARD 1;
T=1.77, F=0.07, N=0.03

Nemacur State	1	2	3	4	5	6	7	8	9	10
1	4	10	10	10	10	10	10	10	10	10
2	4	10	10	10	10	10	10	10	10	10
3	4	2	2	3	3	3	3	3	3	3
4	4	2	2	3	3	3	3	3	3	3
5	4	2	2	3	3	3	3	3	3	3
6	4	2	2	3	3	3	3	3	3	3
7	4	2	2	3	3	3	3	3	3	3
8	4	2	2	3	3	3	3	3	3	3
9	4	2	2	3	3	3	3	3	3	3
10	4	2	2	3	3	3	3	3	3	3

10 = no-till, Nemacur, limited irrigation;

4 = no-till, Furadan, limited irrigation;

2 = no-till, Furadan, dryland;

3 = conventional tillage, Furadan, limited irrigation.

TABLE XI
PRESENT VALUE OF EXPECTED NET RETURNS¹
FOR REGULATORY STANDARD 1;
T=1.77, F=0.07, N=0.03

	(\$ per hectare)									
Nemacur State										
	1	2	3	4	5	6	7	8	9	10
1	2483	2483	2143	2143	2143	2143	2143	2143	2143	2143
2	2483	2483	2143	2143	2143	2143	2143	2143	2143	2143
3	2483	2050	2050	2002	2002	2002	2002	2002	2002	2002
4	2483	2050	2050	2002	2002	2002	2002	2002	2002	2002
5	2483	2050	2050	2002	2002	2002	2002	2002	2002	2002
6	2483	2050	2050	2002	2002	2002	2002	2002	2002	2002
7	2483	2050	2050	2002	2002	2002	2002	2002	2002	2002
8	2483	2050	2050	2002	2002	2002	2002	2002	2002	2002
9	2483	2050	2050	2002	2002	2002	2002	2002	2002	2002
10	2483	2050	2050	2002	2002	2002	2002	2002	2002	2002

¹ Over a 5 year planning horizon, with a 10% discount rate.

-till Furadan control (control 3) has a present value of \$2002.33. That is, the yield increase associated with the limited irrigation scheme (control 3) is not sufficient to exceed the lower machinery cost and irrigation cost savings of control 2. Relative to control 4, both control 2 and 3 have leaching rates sufficiently low to satisfy the standard when control 4 does not. In summary, excluding the states where Nematicur is used, producers must alter their irrigation and tillage practices to maximize returns subject to the imposed standard.

The optimal controls under the regulatory standard which allowed traditional irrigation, only with conventional tillage in conjunction with Nematicur, are provided in Table XII. As could have been expected, the more lenient standard on the use of traditional irrigation provides significantly greater yields than any of the dryland or limited Nematicur or Temik controls. In low initial states of Nematicur and all associated Furadan states, control 11, the traditional irrigation, conventional tillage control is optimal. However, as the initial state of Nematicur increases, the standard becomes binding for the traditional irrigation control and producers switch to control 4 in the lowest Furadan state and control 10 in other Furadan states. associated Furadan states, control 11, the traditional irrigation, conventional tillage control is optimal. However, as the initial state of Nematicur increases, the standard becomes binding for the traditional irrigation

TABLE XII
OPTIMAL CONTROLS FOR REGULATORY STANDARD 2;
T=1.77, F=0.07, N=0.04

Nemacur State	Furadan State									
	1	2	3	4	5	6	7	8	9	10
1	11	11	11	11	11	11	11	11	11	11
2	11	11	11	11	11	11	11	11	11	11
3	11	11	11	11	11	11	11	11	11	11
4	11	11	11	11	11	11	11	11	11	11
5	4	10	10	10	10	10	10	10	10	10
6	4	10	10	10	10	10	10	10	10	10
7	4	10	10	10	10	10	10	10	10	10
8	4	10	10	10	10	10	10	10	10	10
9	4	10	10	10	10	10	10	10	10	10
10	4	10	10	10	10	10	10	10	10	10

11 = conventional tillage, Nemacur, traditional irrigation;

10 = no-till, limited irrigation, Nemacur;

4 = no-till, limited irrigation, Furadan.

associated Furadan states, control 11, the traditional irrigation, conventional tillage control is optimal. However, as the initial state of Nematicur increases, the standard becomes binding for the traditional irrigation control and producers switch to control 4 in the lowest Furadan state and control 10 in other Furadan states.

Control 4 has significantly lower yields than 11, yet has lower irrigation costs, lower machinery costs and lower chemical cost. Once both Nematicur and Furadan violate the standard, control 10 becomes optimal. Control 10 has lower machinery costs than 11, lower yields, lower irrigation costs and equal chemical costs. Control 4 and control 10 differ by chemical costs and have equal machinery and irrigation costs.

The reductions in returns associated with control 11 versus control 4 and control 10 are \$1991.45 and \$2330.96, respectively. That is, producers must use no-till, limited irrigation Furadan or no-till, limited irrigation Nematicur.

The present value of net returns associated with these optimal controls are provided in Table XIII. In the states where traditional irrigation is allowed, the returns are significantly higher than under the first standard scenario; approximately 100.0 percent higher. Also, the lowest present value of net returns is greater than under the first regulatory standard. The lowest present value was \$2050.32 in the first scenario while allowing leaching levels associated with traditional irrigation in conjunction with conventional tillage increases this lowest return to

TABLE XIII

PRESENT VALUE OF EXPECTED NET RETURNS¹
 FOR STANDARD SCENARIO 2;
 T=1.77, F=0.07, N=0.04

Nemacur State	(\$/hectare)									
	Furadan State									
	1	2	3	4	5	6	7	8	9	10
1	4474	4474	4474	4474	4474	4474	4474	4474	4474	4474
2	4474	4474	4474	4474	4474	4474	4474	4474	4474	4474
3	4474	4474	4474	4474	4474	4474	4474	4474	4474	4474
4	4474	4474	4474	4474	4474	4474	4474	4474	4474	4474
5	2483	2143	2143	2143	2143	2143	2143	2143	2143	2143
6	2483	2143	2143	2143	2143	2143	2143	2143	2143	2143
7	2483	2143	2143	2143	2143	2143	2143	2143	2143	2143
8	2483	2143	2143	2143	2143	2143	2143	2143	2143	2143
9	2483	2143	2143	2143	2143	2143	2143	2143	2143	2143
10	2483	2143	2143	2143	2143	2143	2143	2143	2143	2143

¹ Over a 5 year planning horizon, with a 10% discount rate

regulatory standard. The lowest present value was \$2050.32 in the first scenario while allowing leaching levels associated with traditional irrigation in conjunction with conventional tillage increases this lowest return to \$2143.10. This higher return can be attributed to the ability to use no-till, limited irrigation with Nemacur rather than the conventional tillage, dryland Furadan controls.

The third and final regulatory standard to be examined will be one in which the leaching associated with the conjunctive use of traditional tillage and no-till production practices are not allowed. These results are provided in Tables XIV and XV. Here use of Furadan is predominant over Nemacur. This result is not surprising given the greater yields associated with Furadan. Control 5, the conventional tillage, traditional irrigation Furadan control, is optimal for most initial states. However, when the Furadan state gets sufficiently large, control 11, the conventional tillage, traditional irrigation Nemacur control is optimal. When both controls result in the standard being violated, producers must use limited irrigation in conjunction with no-till practices and Furadan -- control 4.

In high states of both Nemacur and Furadan, traditional irrigation is replaced with limited irrigation in conjunction with no-till practices and Furadan. Control 5 has higher yields than 11 or 4 and machinery costs equal to those for control 11 and higher than the machinery costs for control 4.

TABLE XIV
OPTIMAL CONTROLS FOR STANDARD SCENARIO 3;
T=1.77, F=0.095, N=0.04

Nemacur State	Furadan State									
	1	2	3	4	5	6	7	8	9	10
1	5	5	5	5	5	5	5	11	11	11
2	5	5	5	5	5	5	5	11	11	11
3	5	5	5	5	5	5	5	11	11	11
4	5	5	5	5	5	5	5	11	11	11
5	5	5	5	5	5	5	5	11	11	11
6	5	5	5	5	5	5	5	4	4	4
7	5	5	5	5	5	5	5	4	4	4
8	5	5	5	5	5	5	5	4	4	4
9	5	5	5	5	5	5	5	4	4	4
10	5	5	5	5	5	5	5	4	4	4

11 = conventional tillage, Nemacur, traditional irrigation;
 5 = conventional tillage, Furadan, traditional irrigation;
 4 = no-till, Furadan, limited irrigation;

TABLE XV

PRESENT VALUE OF EXPECTED NET RETURNS¹
 FOR STANDARD SCENARIO 3;
 T=1.77, F=0.095, N=0.04

Nemacur State	(\$/hectare)									
	Furadan State									
	1	2	3	4	5	6	7	8	9	10
1	4949	4949	4949	4949	4949	4949	4949	4834	4834	4834
2	4949	4949	4949	4949	4949	4949	4949	4834	4834	4834
3	4949	4949	4949	4949	4949	4949	4949	4834	4834	4834
4	4949	4949	4949	4949	4949	4949	4949	4834	4834	4834
5	4949	4949	4949	4949	4949	4949	4949	4357	4357	4357
6	4949	4949	4949	4949	4949	4949	4949	4357	4357	4357
7	4949	4949	4949	4949	4949	4949	4949	4357	4357	4357
8	4949	4949	4949	4949	4949	4949	4949	4357	4357	4357
9	4949	4949	4949	4949	4949	4949	4949	4357	4357	4357
10	4949	4949	4949	4949	4949	4949	4949	4357	4357	4357

¹ Over a 5 year planning horizon, with a 10% discount rate

Irrigation costs for 5 and 11 are identical while the irrigation costs for the limited irrigation control, control 4, are substantially less.

The ability to use traditional irrigation with each nematicide resulted in substantial increases in present values for the controls. Here the lowest present value was \$4357.37 with control 4.

This regulatory standard has less impact on producer's present value of net returns than any of the standard scenarios. Given the nondiscriminating nature of the standard, it is simply a matter of using the control which includes traditional irrigation in conjunction with no-till practices to maximize net returns. These returns are \$4948.80 and \$4834.95 for controls 5 and 11, respectively.

Consider now the impact on the expected net returns from environmental regulation. The optimal, per hectare unregulated expected net returns and per hectare reductions in present value of expected net returns due to regulation are contained in Tables XVI, XVII and XVIII. Since the chemical states do not influence yields and the controls are invariant to Temik states, these returns can be reported easily. Note that, as the regulatory standards become increasingly strict, the reductions in present values increase.

TABLE XVI
UNREGULATED PRESENT VALUE AND REDUCTIONS IN
PRESENT VALUES WITH REGULATORY STANDARD
1: $F=.07$, $T=1.77$, $N=.04$

[illegible]

TABLE XVIII

UNREGULATED PRESENT VALUE AND REDUCTIONS IN
PRESENT VALUES WITH REGULATORY STANDARD
3: $F=.095$, $T=1.77$, $N=.04$

Unregulated Present Value: \$5,339

Nemacur State	(Reductions in \$/Hectare)									
	Furadan State									
1	390	390	390	390	390	390	390	505	505	505
2	390	390	390	390	390	390	390	505	505	505
3	390	390	390	390	390	390	390	505	505	505
4	390	390	390	390	390	390	390	505	505	505
5	390	390	390	390	390	390	390	982	982	982
6	390	390	390	390	390	390	390	982	982	982
7	390	390	390	390	390	390	390	982	982	982
8	390	390	390	390	390	390	390	982	982	982
9	390	390	390	390	390	390	390	982	982	982
10	390	390	390	390	390	390	390	982	982	982

CHAPTER V

CONCLUDING REMARKS

Summary

A synthesis of computer simulation models and stochastic dynamic programming was proposed to address the problem of subsurface, nonpoint agricultural chemical pollution resulting from peanut production activities in Caddo county, Oklahoma.

Over a five year planning horizon and a discount rate of 10 percent, the imposition of the various regulatory standards resulted in reduced present values of net returns ranging from \$390 to \$3,289 per hectare depending on the particular standard. The inability to satisfy environmental standards when using traditional irrigation resulted in the greatest reductions in present value.

As stated earlier, the optimal controls do not change across Temik states. The cause for this is that given the relative high per hectare costs, lower effectiveness in controlling Root Knot nematodes and the relative propensity for leaching, Temik is never optimal.

Of the management practices examined in this research, the combination of traditional irrigation and no-till tillage result in the highest levels of nematicide leaching. A

viable policy alternative could be to prohibit the conjunctive use of water intensive irrigation schemes, ie. traditional irrigation schemes, and no-till due to enhanced leaching. It is also true, however, that when less irrigation water is used, no-till practices can assist in partially offsetting some of the reduction in yields. This impact is a result of the improved soil moisture retention brought about with no-till. Moreover, the lower machinery costs associated with no-till and the lower irrigation costs associated with the limited irrigation relative to the traditional scheme are beneficial in reducing reductions in net returns.

From an environmental viewpoint, Nemacur is the most desirable nematicide. Though Nemacur's yields are slightly less than those of Furadan, policy makers should provide incentives to adopt the marginally less effective Nemacur over Furadan by granting some advantage to users of Nemacur, perhaps in the form of increase irrigation utilization of no-till practices. These advantages would help offset the lower pest control effectiveness of Nemacur.

Finally, when producers are forced away from an output maximization objective through environmental regulation, cost minimization appears to become a more appropriate firm objective. This new perspective emphasizes the sometimes marginal differences in costs between alternative practices. Close scrutiny of feasible alternatives can assist producers in maintaining net returns even with the imposition of

environmental objectives.

Implications

In general, the production practices which are relatively higher leaching, i.e. traditional irrigation and no-till tillage practices, can also be associated with the highest net returns. Consequently, when environmental constraints on leaching are imposed, producers will be forced away from the practices which provide higher net returns. These adjustments have possible implications for the agricultural economy and resource availability and use.

One of the more drastic adjustments with respect to both yields and leaching is the transition from traditional irrigation schemes to limited or dryland production. The implications for this adjustment are numerous including less use of ground and surface water for irrigation, reduced erosion from irrigation and less marginal land being brought into production. Additional impacts include lower yields and potentially lower farm incomes. As discussed earlier, it appears that no-till production practices can be used to partially soften the impacts of using limited or dryland practices rather than traditional irrigation. This possibility bodes well for soil conservation concerns. That is, in situations where chemical leaching problems render traditional irrigation is environmentally unacceptable, producers can adopt no-till practices, with higher expected net returns than conventional tillage, and be consistent with

soil conservation objectives. On the other hand, using no-till practices with traditional irrigation may greatly increase the leaching rate of farm chemicals.

Temik and Furadan pose greater health and environmental concerns with regard to toxicity than does Nematicur, and they have higher propensities for leaching. In spite of Furadan's and Temik's relative toxicity, sufficient regulation of Nematicur can result in one of these chemicals being selected. Consequently, care should be taken in specifying environmental standards.

The results of this research are dependent on many things including chemicals and soil characteristics, the PRZM and EPIC simulations and costs and returns data. The system of models constructed, could be used to evaluate a variety of similar situations and be useful in the formulation of policy designed to protect ground water resources while minimizing the economic costs to agricultural producers in a study area. Moreover, an idea of the dollar value of management practice incentives including subsidies and taxes designed to reduce chemical leaching can be deduced from the differences in net returns data.

Additional Research

As demonstrated in the literature review, this research represents the first of its type. The uniqueness is due to the dynamic framework used and the number of decision variables facing the producers. However, there are numerous

limitations to this research about which others interested in doing similar work should be aware.

Essential to the costs and returns calculations used is the effectiveness of the chemicals in controlling pests. Additional research is needed on the effectiveness of different application rates. These data would allow researchers to introduce application rate as a decision variable.

Related to the desire to include application rates as a decision variable is the need to link the environmental factors to crop yields. That is, link the impacts of pesticide storage to peanut yields via application rates and/or pest infestation. Also, investigation of optimal irrigation applications both from an economic and environmental viewpoint is needed.

The environmental goal herein was to regulate the quantity of chemical being introduced into the environment. Additional research is needed to link firm level activities to a more specific policy goal such as drinking water standards. This task would require linking methods similar to those used here to a multi-dimensional aquifer model and incorporating health and environmental goals, including drinking water reference doses and maximum contaminant levels.

Most importantly, the need for accurate and accessible data from the physical and natural sciences are paramount to the modelling of subsurface contamination issues. Inputs

into the PRZM model including decay and partition coefficients play a substantial role in predicting leaching. Data are necessary not only for input into simulation models such as PRZM and EPIC, but, just as importantly, as a means of verifying and validating simulations. The relative shortage is in accurate data, not models.

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