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OPTIMIZING WATER QUALITY BENEFITS IN NATURAL RESOURCE POLICY: A MULTI-LEVEL DYNAMIC ANALYSIS

A Dissertation

Presented for the

Doctor of Philosophy

Degree

The University of Tennessee, Knoxville

Robert Rayford Alexander

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DEDICATION

This dissertation is dedicated to my wife

Sheila Kindness Alexander

whose unfailing love and support has made this possible.

ACKNOWLEDGEMENTS

I am indebted to many whose influence and support have made this dissertation possible. Special thanks are due to Burton C. English, major professor, advisor and friend, whose guidance, support, and constructive criticism have been invaluable in completing this dissertation. I would like to express my gratitude to Luther H. Keller, William M. Park, and Alan Schlottmann, graduate committee members, whose assistance in this study and in my graduate career has been most significant. A special acknowledgement is due to Ray G. Huffaker, whose classes in natural resource economics and optimal control theory have served as a technical basis for many of the methods used in this dissertation, as well as inspiration in my career. Thanks are due to Mahadev G. Bhat for his unflagging willingness to review my equations and find those little errors that always seem to escape an author. I thank my wife, Sheila K. Alexander, for tirelessly proofreading and copy editing the manuscript. Finally, I thank my mother, Lucille S. Alexander, whose values, encouragement and inspiration first awakened my desire to pursue a graduate education.

ABSTRACT

Agricultural topsoil is one of the critical natural resources of a civilization. This delicate layer of our planet is the primary source of sustenance for human and animal populations. Arable soil is necessary to feed, clothe, and shelter human beings and is a prerequisite for achieving the aspirations of a society. Without adequate arable land, a civilization will find it difficult to thrive, or even survive (Browning; Napier and Forster). Thus, the potential of a society is largely dependent upon the topsoil of its agricultural lands (Napier and Forster).

While the importance of topsoil and the problem of topsoil loss have long been recognized, over 40 years of cooperative efforts between farmers and the federal government have done little to check the erosion of our farmland (McConnell; Napier and Forster; Rasmussen, 1982; Walker). One-third of U.S. cropland topsoil has been lost in the last 200 years (Walker), and sheet and rill erosion on U.S. cropland continues at a rate of 1.6 billion tons annually (USDA/SCS, 1990).

Increased public awareness of these issues continues to put significant pressure on policymakers to solve our environmental problems while maintaining an abundant, inexpensive food supply. Policy debates, past and present, have focused primarily on physical actions to be taken rather than upon policy goals (Robinson, K.). The primary target for such policy is the "T" level, the "maximum annual number of tons of soil an acre of land can lose indefinitely without impairing the agricultural productivity of the soil" (Crosson, p. 34).

Yet the use of physical goals of soil loss is often challenged by economists who argue that it is not the physical loss from the farm that is important, but the costs incurred by loss of topsoil and offsite damages from agriculturally-generated sedimentation (Robinson, K.). Of the two, offsite sediment damages are far greater than onsite productivity damages. After modeling onsite damages of soil erosion, McConnell (p. 88) concluded "the major impact of soil erosion is water pollution," and "the

problem of water pollution is paramount, not agriculture's future productive capacity." Similarly, Swanson's research in Illinois indicated that the impact of soil erosion on agricultural productive capacity is small.

The costs to society of offsite damages, however, are significant. Sediment is the largest polluter of ponds, streams, rivers and reservoirs (Clark, et al.; Miller and Everett; Wade and Heady; Water Resources Council). Sediment trapped in ditches and lakes reduces water holding capacity and increases the likelihood of flooding. It increases dredging costs of rivers and harbors, fills reservoirs, damages wildlife habitats and diminishes the recreational enjoyment of water resources. The annual offsite cost of erosion in the United States is estimated to be $6.2 billion (Clark, et al.).

Kenneth Robinson (p. 153) states "a shift away from emphasizing physical targets to the use of economic criteria (or some combination of the two) probably would lead to greater returns to society from the dollars currently invested in conservation activities." This study focuses on combining economic and physical relationships to develop a workable policy model to optimize both agricultural revenues and environmental quality.

The specific objective of this study is to develop a soil conservation policy model that incorporates both physical and economic criteria, and that includes the objectives of both producers and policymakers. The model used is an adaptation of the multi-level programming model developed by Candler and Norton and extended by Sylvia and Anderson. A multi-level optimal control model is developed which optimizes the producer's dynamic problem in the first stage, then uses the producer's optimal decision paths in the second stage as components of the policymakers' dynamic problem. The second stage problem utilizes weights indicating the relative importance of the policymaker's competing goals. Those weights are used to construct a dynamic policy frontier demonstrating the relationships between various policy goals and the resulting optimal solution paths.

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CHAPTER I

INTRODUCTION

Agricultural topsoil is one of the critical natural resources of a civilization. This delicate layer of our planet is the primary source of sustenance for human and animal populations. Arable soil is necessary to feed, clothe, and shelter human beings and is a prerequisite for achieving the aspirations of a society. Without adequate arable land a civilization will find it difficult to thrive, or even survive (Browning; Napier and Forster). Thus, the potential of a society is largely dependent upon the topsoil of its agricultural lands (Napier and Forster).

While the importance of topsoil and the problem of topsoil loss have long been recognized, more than 40 years of cooperative efforts between farmers and the federal government have done little to check the erosion of our farmland (McConnell; Napier and Forster; Rasmussen, 1982; Walker). One-third of U.S. cropland topsoil has been lost in the last 200 years (Walker), and sheet and rill erosion on U.S. cropland continues at a rate of 1.6 billion tons annually (USDA/SCS, 1990).

HISTORY OF SOIL CONSERVATION

Early Recognition of Soil Loss

Recognition of soil erosion in the United States dates back more than two and a half centuries to the time when the U.S. was a group of British colonies (Browning; Rasmussen, 1982). In the middle eighteenth century, Jared Eliot wrote of the dangers of "soil washing" and urged farmers to rotate clovers and grasses in cropland (Eliot). Both George Washington and Thomas Jefferson recognized the problem and recommended better management practices including crop rotations, use of clover, and contour plowing (Browning; Rasmussen, 1975; Rasmussen, 1982).

Some Americans continued to speak out about the dangers of soil erosion throughout the nineteenth century. John Lorain and John Taylor urged erosion control, stating that repeated planting of row crops on the same land was the chief cause of erosion (Rasmussen, 1975). In the middle nineteenth century, Edmund Ruffin conducted experiments in the use of marl[1] to control erosion. Ruffin's procedures were successful and others began to adopt his methods, but external pressures for increased production diverted the attention of farmers from soil conservation for almost three-quarters of a century (Rasmussen, 1982).

The primary cause of these pressures was the Civil War. Labor was scarce and demand for food products was high. The resulting high prices created a shift from human to animal power on the farm and a westward population expansion. The passage of the Homestead Act of 1862 launched the first agricultural revolution on this continent (Rasmussen, 1982). Following the Civil War, the pressure for increased production continued as farmers tried to pay off debts created by increased technology and land expansion.

These pressures, both during the war and after, resulted in production being placed before conservation. Some were aware of the problem, however, and tried to urge farmers to conserve soil. An 1894 United States Department of Agriculture bulletin entitled, *Washed Soils: How to Prevent and Reclaim Them*, noted that thousands of acres of useful but eroded cropland were abandoned each year (Rasmussen, 1982). Two 1910 United States Department of Agriculture bulletins, *Soil Conservation* and *Corn Cultivation*, advised farmers that soil conservation was vital to the continued productivity of their land (Rasmussen, 1982).

Despite farmers' unwillingness to sacrifice current production for future productivity, a movement in academic and political circles was beginning to form. In 1914, M. F. Miller of the University of Missouri conducted the first comprehensive experiments trying to determine the nature of erosion. He collected runoff in concrete tanks to measure and characterize the resulting soils

[1]Marl is a mixture of clay and carbonate of lime. Ruffin primarily used this in the form of fossil shells.

(Browning). In 1928, a United States Department of Agriculture bulletin entitled, *Soil Erosion: A National Menace*, was published in which the author, Hugh Hammond Bennett, declared soil erosion to be a national problem. He stated, "our population may feel acutely the evil effects of this scourge of the land, now largely unrestrained" (Rasmussen, 1975). One year later, following pressure from Bennett and others, Congress passed an amendment to the Agricultural Appropriations Act of 1930 allocating $160,000 to study soil erosion, its cause, and its control. Bennett was placed in charge of the program which established ten regional soil erosion experiment stations. This was the beginning of soil and water conservation research as we know it today (Baker, et al.).

Evolution of Modern Soil Conservation Policy

The Soil Erosion Service was established as a branch of the Department of the Interior in 1933. This new agency established cooperative research projects with many state agricultural colleges. Two years later, it was transferred to the Department of Agriculture. Congress passed the Soil Conservation Act that same year which permanently established the soil conservation program and renamed the old Soil Erosion Service the Soil Conservation Service.

The dustbowl era of the early 1930's helped to focus public attention on the problem of erosion, and for the first time farmers were actively involved in soil conservation activities on a large scale. Between 1935 and 1947, all the states passed legislation setting up soil conservation districts to assist farmers in conservation efforts. The Soil Conservation Service sent experts into these local offices to disseminate the information gathered through research at the experiment stations.

The Agricultural Adjustment Act of 1933 provided for the control of agricultural production to meet demand, but this provision was declared unconstitutional by the Supreme Court in 1936 (Rasmussen, 1982). In the meantime, the Soil Conservation Service was developing a plan to encourage farmers to voluntarily shift production from erosive crops to soil-conserving cover such as legumes and grasses. Farmers would receive soil-conserving payments for shifting from erosive to non-erosive crops, and soil-building payments for enacting soil-building practices on cropland or pasture. In 1936, Congress adopted such a plan in the Soil Conservation and Domestic Allotment Act. Known as the Agricultural Conservation Program, this plan provided the dual benefits of reducing erosion and controlling excess production. The Agricultural Conservation Program, in some form, has persisted to this day as a major soil conservation policy tool.

The Agricultural Conservation Program, however, has not been without its critics. Early in the program, cost sharing was provided for production-oriented as well as for conservation-oriented improvements. During the early 1950's, the Secretary of Agriculture attempted to eliminate production-oriented practices from the program. Those efforts failed, yet the momentum for such reform continued until achieving success near the end of the 1970's. The Food and Agriculture Act of 1977 specified, "eligibility for assistance under the Agricultural Conservation Program would be based upon the existence of a conservation or environmental problem that reduced the productive capacity of land and water resources or caused environmental degradation" (Rasmussen, 1982). The move away from supporting production-oriented practices was finalized in 1980 with new United States Department of Agriculture regulations, "that cost-sharing will not be used for carrying out measures and practices that are primarily production oriented or that have little or no conservation or pollution benefits" (USDA/ASCS).

While the Agricultural Conservation Program was under fire in the 1950's, Congress was developing a new approach to supply-control and conservation policy. The Soil Bank Program, established by the Agricultural Act of 1956, provided for control of excess production and soil erosion by removing large amounts of land from agricultural production. The program was composed of two distinct provisions: the acreage reserve and the conservation reserve.

The acreage reserve provision was designed to reduce the acreage planted in allotment crops such as wheat, cotton and corn. Under this program, farmers received payments for diverting acreage from these crops to conservation cover. By 1957, the acreage reserve enrolled 21.4 million acres (Rasmussen, 1982).

The conservation reserve provision was open to all farmers who would contract to place their cropland into conservation usage for up to ten years. In 1960, 28.6 million acres were placed in the conservation reserve of the Soil Bank Program (Rasmussen and Baker). One criticism of the conservation reserve was that the tendency of some farmers to enter entire farms into the program caused hardship for rural communities economically dependent upon farming. The last conservation reserve contracts under the Soil Bank Program were issued in 1960. From the end of the Soil Bank Program until the middle of the 1980's, conservation policy was once again primarily governed through Soil Conservation Service programs and the Agricultural Conservation Program (Rasmussen, 1982).

As if in prelude to the changes that would take place in 1985, the late 1970's brought significant research resources to bear on the soil conservation problem. The Soil and Water Resources Conservation Act of 1977 (RCA) directed the United States Department of Agriculture to appraise the status of the nation's soil, water and related resources and to prepare a program for furthering the conservation of these resources (Rasmussen, 1982). The Agricultural Stabilization and Conservation Service was directed by the president to review and evaluate the Agricultural Conservation Program. The Soil Conservation Service conducted the 1977 National Resources Inventory on the use and quality of our nation's land. The Water Resources Council published its second National Water Assessment in 1978, and in 1979 the National Agricultural Lands Study was set up to study the conversion of agricultural land to nonagricultural uses. While these studies varied somewhat in detail, they all agreed that substantial amounts of land suffer from serious erosion and that the potential exists for even more serious problems in the future (Rasmussen, 1982; USDA/ASCS; USDA/SCS, 1989).

The Food Security Act of 1985 represented some major changes in farm legislation. While previous farm bills have tended to define farm support levels precisely, this bill provided significant discretionary power to the Secretary of Agriculture to make such determinations. It also demonstrated a movement toward the consideration of broad social goals as well as those arising from the farm sector. Subtitle XII of the act addresses soil and water conservation issues through three specific programs: the Agricultural Conservation Program, the Conservation Reserve Program, and the Conservation

Compliance Provision. These programs have been continued or expanded in the Food, Agriculture, Conservation, and Trade Act of 1990.

The Agricultural Conservation Program, as previously discussed, has been in existence in some form since the 1930's. The program provides for cost sharing with farmers in implementing conservation and protection practices on agricultural land. Practices eligible for technical and cost sharing assistance include conservation cropping systems, water diversion and containment, wildlife protection and enhancement, and forest-timber protection and maintenance (Thompson, et al.).

The Conservation Reserve Program is conceptually similar to the conservation reserve provision of the Soil Bank Program of the 1950's. The stated objectives of the program are to (a) reduce water and wind erosion, (b) protect our long-term capability to produce food and fiber, (c) reduce sedimentation, (d) improve water quality, (e) create better habitat for fish and wildlife through improved food and cover, (f) curb production of surplus commodities, and (g) provide needed income support for farmers (Reichelderfer and Boggess). Farmers are encouraged to discontinue intensive use of highly erodible cropland and convert the land to permanent vegetative cover through placement of land into the Conservation Reserve Program through a bid mechanism. Annual payments of up to $50,000 per farm per year are administered through the Agricultural Stabilization and Conservation Service. Cost sharing is also available for establishment of permanent vegetative cover (Thompson, et al.).

Eligibility of cropland for the Conservation Reserve is limited to highly erodible cropland on which crops have been grown at least two years out of the past five. To be considered highly erodible, cropland must have an erodibility index greater than or equal to eight for wind or water erosion, and must have produced erosion rates greater or equal to "T" while cropped. The erodibility index, a measure of the inherent potential of a soil to erode, is based on soil type, slope, rainfall, and wind exposure (Thompson, et al.). For a field to be entered in the Conservation Reserve Program, at least two-thirds of the field must be highly erodible by these criteria.

The current Conservation Reserve Program addresses one of the concerns generated by the old Soil Bank program in that it limits the amount of land that may be entered in the reserve within any one county to 25 percent of the total cropland (FSA85). This provision reduces the potential for economic hardship within the rural community as a result of the program.

The Conservation Compliance Provision was enacted, in part, to reduce sediment from erosion and to improve water quality. This provision discourages production of crops on highly erodible cropland. Where highly erodible cropland comprises more than one-third of a field, the farm operator must develop an annual conservation cropping system plan. The plan must be developed by 1990 and fully implemented by 1995. Failure to develop and implement such a plan results in the ineligibility of the farmer for (a) any type of price support payment, (b) farm storage facility loans, (c) federal crop insurance, (d) federal disaster payments, (e) Farmer's Home Administration loans, or (f) payments through the Commodity Credit Corporation (FSA of 1985). The Conservation Compliance Provision represents the first time that Congress has tied soil and water conservation directly to eligibility for other agricultural programs.

Current and past policies have been oriented toward keeping soil in place through changes in land use. Such policies have not been designed to consider the cost of erosion to society.

THE EROSION AND SEDIMENTATION PROCESS

Sediment is a product of soil erosion. Its sources include croplands, grass lands, forests, construction sites, surface mines, roadways, urban areas, stream channels, incised valleys, and active gullies (Robinson, A.). Sedimentation is a function of soil erosion, land characteristics between the erosion site and the stream, and stream transport characteristics. Sediment follows a downstream course in waterways, slowly moving toward the oceans. Eroded soil generally moves small distances, perhaps as little as a few meters each year (Robinson, A.), so that sediment generated in a watershed is only a fraction of total erosion.

Figure 1.1 shows the determinant factors of the sedimentation process and their interrelationships. Sediment delivery determines the amount of manmade erosion that actually reaches the streambed as sediment while sediment transport determines the movement of that sediment within

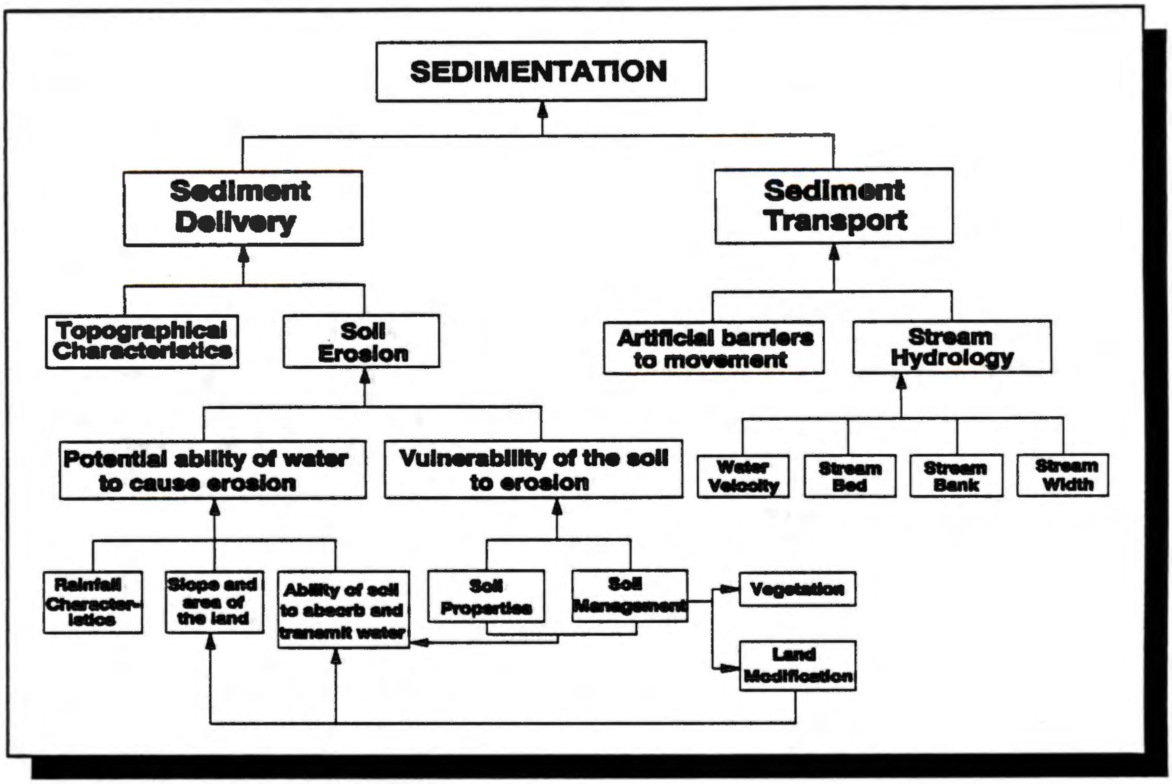

Figure 1.1. The sedimentation process.

the water system as well as natural erosion of stream banks which occurs without human intervention. The principal engine of the sedimentation process is erosion. The degree of erosion on given land is a function of the potential ability of water to cause erosion and the vulnerability of the soil to erosion. The frequency and force of rainfall and the slope and area of the land contribute to the potential of water to cause erosion. In addition, the ability of soil to absorb water is a major factor. Non-absorbent soil is more likely to erode than absorbent soil. The vulnerability of the soil to erosion is influenced by the specific properties of the soil itself and by management practices of the land in question. Such factors as vegetative cover and physical modifications to the land can have a significant effect on erosion. As shown in Figure 1.1, there are also interrelationships between many of the specific elements of the erosion process. Soil properties and management affect the ability of the soil to absorb water, and land modification affects both that ability and the slope and area of the land. However, not all eroded soil will become sediment. Once erosion has occurred, the topographical characteristics of the land between the erosion site and the waterway will determine how much, if any, of that soil reaches a waterway.

After soil reaches the stream, the sediment transport system determines the movement and impacts of the sediment. Depending upon the specific stream hydrology, the movement may be relatively fast or extremely slow. Such factors as water flow, width of the stream, and streambed and bank composition will determine the pace with which sediment moves downstream. In addition, artificial barriers may impede movement of sediment or stop it altogether. Manmade lakes, artificial embankments, and dams can act as collection sites for sediment that may otherwise have continued downstream.

The costs of erosion may be categorized in two broad classifications: onsite and offsite. The loss of topsoil from the land itself reduces the productivity of the land, requiring the farmer to substitute other inputs such as fertilizer to maintain production. These onsite costs may take the form of lower production, the cost of fertilizer application, or the cost of adopting production practices that prevent or reduce erosion. Offsite costs result from the sediment in waterways. These costs include damages from the presence of the physical sediment as well as from chemicals and nutrients carried into the waterway by the sediment. Offsite costs of erosion are significantly greater than onsite costs (McConnell; Swanson, 1979).

Once eroded soil has reached the water as sediment, offsite damages of some type will be incurred. The only way to prevent sedimentation and its related damages, therefore, is to focus policies at or below the soil erosion or topographical characteristics levels of Figure 1.1. A close examination of the figure will indicate that soil management is the only determinant of soil erosion which may be readily controlled. Sharp and Bromley remind us, "it is the practices of plowing, fertilizing, harvesting, and manure spreading that provide the inputs into a process which is essentially driven by hydrological phenomena" (p. 593). Controls may be plant-based through crop rotations, or shifting of highly erodible land to less erosive uses; residue-based through methods such as conservation tillage, ridge tillage, or no till; or structure-based through such practices as contouring or terracing. Some control also may be exerted at the topographical characteristics level. An example of such control is that of grass filter strips bordering streams. These buffer the erosion, trapping soil before it reaches the waterway. Practices that reduce total erosion, rather than just the movement of eroded soil, have the added benefit of reducing both onsite and offsite erosion costs.

THE SOIL EROSION PROBLEM TODAY

Increased public awareness of the soil erosion problem continues to put significant pressure on policymakers to solve our environmental problems while maintaining an abundant, inexpensive food supply. Policy debates, past and present, have focused primarily on physical actions to be taken rather than upon policy goals and objectives (Robinson, K.). The primary target for such policy is the "T" level, the "maximum annual number of tons of soil an acre of land can lose indefinitely without impairing the agricultural productivity of the soil" (Crosson, p. 34).

Yet the use of physical goals of soil loss is often challenged by economists who argue that it is not the physical loss from the farm that is important, but the costs incurred by loss of topsoil and offsite damages from agriculturally-generated sedimentation (Robinson, K.). Of the two, offsite sediment damages are far greater than onsite productivity damages. After modeling onsite damages of soil erosion, McConnell (p. 88) concluded "the major impact of soil erosion is water pollution," and "the problem of water pollution is paramount, not agriculture's future productive capacity." Similarly, Swanson's (1979) research in Illinois indicated that the impact of soil erosion on agricultural productive capacity is small.

The costs to society of offsite damages, however, are significant. Sediment is the largest polluter of ponds, streams, rivers and reservoirs (Clark, et al.; Miller and Everett; Wade and Heady, 1977; Water Resources Council). Sediment trapped in ditches and lakes reduces water holding capacity and increases the likelihood of flooding. It increases dredging costs of rivers and harbors, fills reservoirs, damages wildlife habitats and diminishes recreational enjoyment of water resources. The annual offsite cost of erosion in the United States is estimated to be $6.2 billion (Clark, et al.).

Kenneth Robinson states "a shift away from emphasizing physical targets to the use of economic criteria (or some combination of the two) probably would lead to greater returns to society from the dollars currently invested in conservation activities" (p. 153). Recently, more attention has been paid to combining the economic and physical components of agricultural pollution problems. For example, the Conservation Compliance Provision of the Food Security Act of 1985 was originally to be administered under the Basic Conservation Systems requirements as indicated in local Soil Conservation Service Field Office Technical Guides. The Basic Conservation Systems criteria enumerate conservation practices that are considered to adequately control cropland erosion (Thompson, et al.). However, the state conservationist has been granted authority to establish less stringent Alternative Conservation Systems where soil types, economic conditions, social customs, religious beliefs, or managerial abilities prevent the adoption of Basic Conservation Systems (Thompson, et al.).

The adoption of Alternative Conservation Systems indicates recognition of the economic relationship between erosion control and costs. The erosion control/cost relationship, as shown in Figure 1.2, has been both theoretically and empirically established (Braden, et al.; Ervin, et al.; McConnell; Moffitt, et al.; Park and Sawyer; Saygideger, et al.; Taylor and Frohberg). At high erosion rates, the unit cost of reducing erosion may be very small while the unit cost of a reduction at lower levels may be prohibitively expensive. A reduction from E_3 to E_2 in Figure 1.2 will cost $(C_2 - C_1)$, while a reduction from E_2 to E_1 will cost $(C_3 - C_2)$.

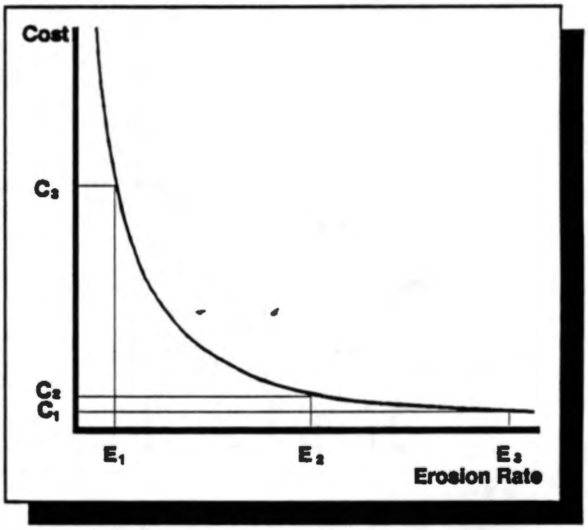

Figure 1.2. Cost curve for erosion reduction.

Given two farms, both producing erosion at rate E_3, a farm for which "T" is E_2 may be economically able to meet the Basic Conservation Systems requirements while another farm for which "T" is E_1 may be unable to meet the requirement and remain in production. In the latter case, the farm would be likely to withdraw from federal programs altogether rather than cease production. Presumably, the farmer would continue to create erosion at E_3. Under Alternative Conservation

Systems, however, the farmer may be allowed to reduce the erosion rate to E_2 although it does not meet the "T" standard. Society gains the benefit of some erosion reduction rather than none.

This illustration demonstrates the contrast between physical and economic policy. The physical policy which considers only the actual "T" value may well result in less reduction, through nonparticipation, than the economic policy. Economic policy, by recognizing the increasing marginal cost of erosion control, can come closer to optimizing both private and public expenditures.

OBJECTIVE OF THE STUDY

This study focuses on combining economic and physical relationships to develop a workable policy model to optimize both agricultural revenues and environmental quality. The specific objective of this study is to develop a soil conservation policy model, incorporating the objectives of both producers and policymakers, that: 1) estimates the economic transfers between agricultural producers and society resulting from agricultural production and its associated sediment-based externalities, and 2) estimates a socially optimal level of taxation, given varying levels of perceived importance to society of agriculture versus environmental quality. The model used is an adaptation of the multi-level programming model developed by Candler and Norton and extended by Sylvia and Anderson. A multi-level optimal control model is developed which optimizes the producer's dynamic problem in the first stage, then uses the producer's optimal decision paths in the second stage as components of the policymakers' dynamic problem. The second stage problem utilizes weights indicating the relative importance of the policymaker's competing goals. Those weights are used to construct a dynamic policy frontier demonstrating the relationships between various policy goals and the resulting optimal solution paths.

CHAPTER II

LITERATURE REVIEW

MODEL STRUCTURE IN SOIL CONSERVATION RESEARCH

The last two decades have brought significant research efforts to bear on the problem of soil erosion. This may have been partially triggered by the agricultural output expansion of the 1970's and the resulting increase in erosion (McConnell). Yet there is little evidence that either research or government assistance programs have significantly reduced erosion on cropland in production. Lee states that increasing soil losses are "intensifying air and water pollution problems and reducing the productivity potential of . . . cropland" (p. 1070).

Several theories have been proposed to explain why farmers continue to tolerate erosion on their cropland. Burt suggests that farmers do not act to prevent erosion because they can substitute other inputs for soil depth. This relationship is also modeled by McConnell who concludes that the optimal policy for the farmer may include exhaustion of the topsoil. Wade and Heady (1979) propose that conservation practices are not adopted because "even though the practices may provide higher long run profits . . . the savings are simply not worth the change . . ."(p. 1281). Renard, et al. suggest "farmers are simply too busy with the many other problems" (p. 1278).

The contrast between conservationists' objectives and farmers' actions suggests market failure. Wade and Heady (1979) recognize two externalities from soil erosion, "potentially reduced agricultural production capacity and the pollution of the eroded soil" (p. 1281). Most modeling efforts to date, regardless of model structure, have addressed one or both of these externalities.

Mathematical Programming Models

Numerous mathematical programming models have addressed the problem of soil erosion in the last two decades. These models offer unparalleled flexibility in addressing a wide variety of problems. Mathematical programming models are useful for examining any problem which involves optimizing one or more objectives while recognizing given resource constraints. Mathematical programming models used in soil erosion research have evolved from linear programming models to associated forms such as separable, dynamic or quadratic programming. All of these forms are still in use in applied conservation research today.

The late 1970's and early 1980's saw the development of several large linear programming models used in erosion control research. Taylor and Frohberg used a large linear programming model of crop production in the corn belt to estimate the partial welfare effects of alternative environmental controls. The environmental controls included erosion control, banning of insecticides or herbicides, and limiting nitrogen application. The model estimated consumer and producer surplus but did not consider the environmental benefits of such control policies. Wade and Heady (1977) used a similar model to examine the management changes which might be required to implement several hypothetical erosion control policies. English and Heady used two large-scale linear programming models to compare the short-run and long-run effects of various erosion control measures. Policy implementation was simulated by restricting soil loss to multiples of the "T" level. The results indicated that farmers may well make decisions based upon short-run cost-price pressures rather than upon long-run soil conservation concerns. Osteen and Seitz used a linear programming model to predict regional production shifts which might occur with the implementation of erosion control policies, and English used a large linear programming model to examine several levels of allowed soil loss and project the impacts of each to the year 2030.

In other studies, linear programming models were used in a less straightforward way or for less straightforward purposes. Moffitt, et al. used linear programming as the basis for their model which compared the efficiency of taxes to emissions standards in pollution control. Horner used a multi-period linear programming model to optimize returns subject to given nitrogen emissions standards for an infinite planning horizon. Miller and Everett examined the economic impact of controlling sediment loss through changing forest management practices. They used a two-stage model in which a linear programming component first optimized management strategies, then used the results as input to an input/output model to examine the regional impacts of such changes.

Though not as prevalent as linear programming, other mathematical programming techniques have also been used to study erosion problems. Although the exact algorithm varies, a common theme was the examination of multiple simultaneous objectives. Frohberg and Swanson used a dynamic programming model to determine the optimum rate of soil erosion in one watershed in Illinois. By including sediment damage in the model, they were able to consider simultaneously both crop production and sedimentation from soil erosion. Boggess and Heady used a separable programming model to analyze the potential of alternative policies to achieve simultaneously the dual goals of increased farm income and reduced soil erosion. This study focussed on land retirement as a tool for reducing erosion. Kramer, et al. used a quadratic programming model to examine the influence of risk on farm-level soil conservation decisions. The model allowed the simultaneous consideration of uncertainty in revenues and input supplies. In still a more complex framework, Schatzer, et al. used a hybrid Econometric/Tâtonnement programming model to approximate equilibrium prices and quantities of agricultural commodities for the year 2000. Although an examination of soil loss was not the primary purpose of the study, erosion factors were integral to the model and could well be addressed through such methodology.

Mathematical Models

Many researchers have modeled soil conservation using static or dynamic neoclassical economic models. Eleveld and Halcrow defined a Pareto-optimal framework in which they maximized net social income under a variety of conditions. They began with the case of no resource depletion or offsite damages and progressed to the case in which both resource depletion and offsite damages were present.

While the model explicitly considered time, it was more of a static model than dynamic. The objective function of the model was summed over time and discounted, but the effect of one production period on the next was not modeled. Reichelderfer and Boggess used a neoclassical model in which a decision-maker's utility was maximized as a function of various competing objectives. The Conservation Reserve Program was analyzed for alternative bid selection criteria. Sharp and Bromley developed a multilevel neoclassical constrained optimization model in which both producer and policymaker objectives are simultaneously optimized. The producer sought to optimize profit while the policymaker optimized water quality. The model was static, however, and did not provide for the policymaker to assign value to agricultural production as well as water quality.

Dynamic models have tended to concentrate on onsite effects of soil erosion rather than offsite effects. Van Kooten, et al. used a dynamic Markov decision model to develop a trade-off function between the various objectives of the farmer. The model examined how optimal management practices are affected by varying levels of concern for stewardship. This model of Canadian agriculture did not consider the imposition of conservation policy by the government. Walker developed a dynamic model comparing conventional farming to conservation practices in their effects on onsite soil loss damage. The model sought to determine the point at which farmers would adopt conservation practices in response to decreasing soil depth and productivity. McConnell introduced soil depth and soil loss into an optimal control model of agricultural production to determine when the private path of erosion differs from the socially optimal path. The study indicated that a farmer may rationally choose to produce in such a manner as to deplete soil resources. Both Walker and McConnell restricted their research to onsite effects of erosion. It is quite possible that the results of McConnell's study would have been significantly different if external costs were internalized to the farmer.

DEVELOPING A SOIL EROSION POLICY MODEL

The research reviewed here demonstrates the extensive literature on the regulation of watershed resources. The dominant analytical styles in the research include both conditional and optimization analyses. Conditional analyses examine a set of assumed parameters and policy variables to determine the results of such conditions. Optimization analyses seek to determine the most efficient use of resources without necessarily making a priori determinations of the level of policy involvement. Many research efforts contain elements of both. A basic premise of this work is that several specific elements are necessary for the development of a soil erosion policy model. Those elements include modeling (1) the interaction of producer and policymaker (Anderson and Lee; Candler, et al.; Candler and Norton; Sharp and Bromley; Sylvia and Anderson), (2) the dynamic nature of the sedimentation process (Ervin, et al.; Rausser, 1980; Swanson, 1982), and (3) the recognition of multiple, competing goals of the policymaker (Rausser and Yassour; Sylvia and Anderson; Van Kooten, et al.).

None of the reviewed models included all of these elements. This study is intended to develop a modeling framework which does. The following sections examine each of these elements and their particular contribution to a erosion policy model.

Interaction of Producer and Policymaker

Multi-level Models

While a production model may examine the optimal choices of a single decision-making producer, a model of policy regulation must consider both the producer and the policymaker. Sharp and Bromley state "the essence of efficient policy for dealing with agricultural pollution, where efficiency comprehends not only least-cost abatement at the firm level but also the allocation of scarce public funds, is that of coordinating the actions of two primary actors: the agricultural firm and the management agency" (p. 594). Anderson and Lee point out that research on regulatory policy designed to correct open-access market failure usually examines only the optimal level of pollutant released into a watershed. Models are built with production of the pollutant as the control variable. Yet the policymaker does not have direct control over production of pollutant. He has control only over the regulatory instrument itself. Thus, the control variable for the producer is production, but the control variable for the policymaker is the governing instrument.

This difference is based not only upon the actual instrument under control by each actor, but by the underlying dichotomy between their goals and objectives. The goal of the producer is frequently assumed by economists to be profit maximization (Van Kooten, et al.; Henderson and Quandt). The goal of policy analysts is to develop economic policy instruments consistent with the public interest. Such instruments must attempt to reconcile the differing values and objectives of a variety of user groups and then provide the means for implementing chosen objectives (Robadue, et al.).

A recently developed modeling approach which explicitly recognizes these needs is multilevel programming. Developed by Candler and Norton in 1977, multi-level programming is intended to optimize a system of "two separate decision makers in hierarchical relationship, each with his own objective function and control over distinct but interacting variables" (Candler, et al.).

This concept would appear to hold significant potential for applied policy analysis, yet Candler, et al. found less than satisfactory results in attempting to analytically or numerically solve empirical problems. They state "the two-level nature of most policy problems mean that they are not generally amenable to solution by mathematical programming. Furthermore, solutions obtained by dint of ignoring the behavioral, or lower level, decision function are likely to be seriously misleading." Candler, et al. contrast multi-level programming with optimal control theory, stating that "control theory deals with a dynamic system while multi-level programming deals with a static equilibrium." While true, they neglected to consider the possibility of combining a multi-level analysis with optimal control theory to solve dynamic policy problems.

This was later accomplished by Sylvia and Anderson, who developed an analytical system for net-pen aquaculture development. No empirical work was performed, but the framework was established for the practical use of multi-level optimal control models. Another benefit of this type of model is the ability to develop a solution independent of policy goals. Accordingly, an optimal policy frontier may be developed to demonstrate the tradeoffs between different policy goals. This approach "does not require the prior articulation of policy preferences, and by parameterizing on policy goals it allows policy frontiers to be generated which provide a configuration of tradeoffs and policy options suitable for use by decision makers and other policy actors" (Sylvia and Anderson, p. 2). The multi-level optimal control approach is the basis for the model developed in this dissertation.

Taxes as a Policy Instrument

Taxes have been studied extensively as a policy instrument for internalizing external costs arising from natural resource use, yet they have not been implemented in any agricultural setting. Virtually all environmentally-oriented agricultural policy to date has involved the use of subsidies and cost-sharing to encourage environmentally sound behavior. The Agricultural Conservation Program provides cost-sharing with farmers who choose to make conservation-oriented improvements to their land. The Conservation Reserve Program leases highly erodible cropland from farmers to remove the land from production. The first land-based programs to hold farmers accountable for environmental abuse without transferring the cost to society are the Conservation Compliance, Swampbuster, and Sodbuster provisions of the Food Security Act of 1985. These programs still do not assign the external costs of production to the farmer, but they do provide the threat of removing existing subsidies if guidelines are not met.

Despite the apparent political infeasibility of taxation as a policy tool for reducing agricultural pollution, economists continue to advance the concept as both valid and efficient. Sharp and Bromley noted "agricultural economists have adhered tenaciously to this methodology, to the extent of being tendentious" (p. 592). The predisposition of economists toward taxes is firmly based in economic theory. Pigou proposed that external effects were a cause of suboptimal economic output levels. His solution included the imposition of taxes or subsidies to equate prices with marginal social costs[2] (Horner). Coase argued that where nonattenuated property rights exist and where transactions costs are absent, negotiations between involved parties will remove Pareto-relevant externalities and provide an efficient

[2]In the Pigouvian framework, marginal social costs are equal to marginal external costs plus marginal private costs.

solution (Randall). In light of the acknowledged existence of significant transactions costs, most of the literature since Coase's time has defended policies based upon Pigouvian taxes or subsidies. These policies eliminate the need to consider the interference of transaction costs or ambiguous property rights in natural resource issues (Horner).

Baumol showed that Pigouvian taxes or subsidies are necessary for optimal allocation of resources and that neither compensation nor taxation should be applied to those affected by the externality. A tax on soil loss was shown by Taylor, Frohberg, and Seitz to result in the most efficient way of achieving a desired reduction in soil loss. Taylor and Frohberg found "the least costly method of achieving a specified level of soil loss is a tax" (p. 33). Horner stated that a specific water quality goal can be met at minimum cost through a system of charges against emitters.

In spite of such strong support for tax-based policies, policymakers have continued to use emission standards to achieve environmental goals. Possible explanations for policymakers' preference for emissions-based tools include a lack of understanding of alternatives (White), the uncertainty of the level of charges that would be required to meet the policy goals (Horner), and the political influence of firms to direct a preferential policy (Buchanan and Tullock).

While the debate over the use of taxation as a policy instrument is important, it is not necessary to determine the relative merits of either argument to accept the value of a tax-based model. The level of taxation required to optimize both producer and policymaker goals in soil conservation is developed in this study. That optimal tax level--or one derived from further application of the model--could conceivably be used as the basis for a tax-based policy, yet the economic information derived from such an analysis is valuable in its own right. The optimal tax level resulting from this model is an economic measure of the level of externality imposed upon society by agricultural production. This optimal tax, if not imposed, may be thought of as an involuntary transfer from society as a whole to the agricultural industry.

Another consideration in the application of this model is that the model itself does not constrain the optimal tax to be positive. The optimal transfer may not be a tax on farmers, but a subsidy to farmers. The model demonstrates the change in optimal tax as society places relative values on agriculture versus the environment. It is entirely possible that as the relative value becomes strongly skewed toward agriculture, the optimal tax will become negative--effectively a subsidy. In terms of this model, it should be noted that the movement in recent years to lower agricultural subsidies and to place the responsibility of certain environmental conditions on the farmer may be interpreted as such a shift of priorities away from agriculture and toward environmental quality. Therefore the use of taxation as a policy instrument is not constrained by a lack of political acceptance, but is a useful measure of economic value whether or not the policy being modeled is ever considered for enaction.

The Dynamic Nature of Sedimentation

Sediment as a Dynamic Process

Ervin, et al. state "conservation programs...should be evaluated relative to some hypothetical 'optimal' erosion control solution which maximizes net social benefits" (p.274). Since the sedimentation process is inherently dynamic in nature, such an "optimal solution" would necessarily be derived from a model which explicitly recognizes soil as both stock and flow resource. Rausser (1980) states "management of the soil resource is inherently dynamic and thus, static constructs modified by various bells and whistles provide little insight" (p. 1094). The on-farm erosion problem and the off-farm sedimentation problem can be thought of as dual specifications of the same process. The producer's objective is maximization of revenues subject to soil loss constraints, while society's objective is minimization of soil accumulation subject to revenue constraints. Thus, the underlying dynamic structure of the soil loss problem is invariant to the question of on-farm versus off-farm effects.

In referring to the on-farm problem, Rausser (1980) advances that soil conservation is a problem in capital theory whose operational implementation is the management of soil resources over time. He states "soil is not a single resource but a set of individual interrelated components which have both stock and flow dimensions" (p. 1093). It is exactly this aspect of the soil loss process, the interrelationships of both stock and flow resources over time, that demands an explicitly dynamic methodology such as optimal control theory. Swanson states "any discussion of the socially optimal rate of soil conservation should include mention of the application of control theory" (p. 252).

The application of control theory to soil loss problems began in the 1970's and has increased since that time. Analytical solutions to control theory models have been derived through a variety of techniques such as approximately optimal decision rules (Burt and Cummings) and the Pontryagin conditions[3] of formal optimal control theory. In 1977, Burt and Cummings analyzed the steady state associated with socially optimal natural resource use. In the same year, Frohberg and Swanson derived the optimal levels of soil loss, considering offsite damages, discount rates, and various demand scenarios. McConnell subsequently used optimal control theory to model the private and social utilization of soil.

Given the important role of optimal control theory in the analysis of soil loss problems and the role this methodology plays in this analysis, a detailed description of the tool seems appropriate.

Optimal Control Theory in Economics

The foundations of optimal control theory reach back to the eighteenth century in the rather arcane discipline of the calculus of variations. Limited in scope, the calculus of variations was all but ignored by economists into the twentieth century. Capital theory, the study of the economics of time, lacked the serious tools necessary to fulfill its potential as a valuable sub-discipline of economics (Robinson, J.). While time was introduced into economic theory in the era of classical economics by such economists as Böhm-Bawerk (Ekelund and Hébert; Schumpeter), the basis of analysis was still primarily static in nature. In 1958, however, Russian mathematician L. S. Pontryagin introduced the basic principles of optimal control theory (Pontryagin, et al.). This theory generalized the calculus of variations, providing the tools necessary for economists to explore capital theory in ways which had not previously been possible.

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[3]See the section entitled "Optimal Control Theory in Economics" in this chapter for a detailed derivation of the Pontryagin conditions.

Since that time, the use of optimal control theory in economics has expanded from the traditional examination of economic capital to the examination of growth in many sub-disciplines of economics. One such use to which these tools have been put is the examination of pollution abatement questions and the economic evaluation of alternative possible actions where pollution is a problem. Pollution is a unique application of the theory as the stock involved does not grow naturally, but decays; and the "capital," the pollution stock, does not bring profits, but social and economic costs.

The Pontryagin Conditions[4]

Consider the decision problem of a society or firm that wishes to minimize the damage costs of some type of waterborne pollution. Assume this pollutant is contained within a lake and that the damage from the pollutant is restricted to the lake.

At any date, t, a certain stock of pollution exists due to the past activities and decisions of the firm.[5] Denote the pollution stock as $p(t)$. Given this pollution stock p at time t, the firm must make decisions concerning the rate of pollution inflow, rate of pollution removal, etc. For the purposes of this exposition, we will consider the rate of pollution inflow to be fixed--that is, beyond the control of the firm--and will assume the firm can control only the rate of pollutant removal at a given time, denoted by $r(t)$.

From the inherited pollution stock at a given date and the current removal decisions, the firm incurs a certain cost per unit of time. Denote this cost function as $c[p(t),r(t),t]$[6], where c determines the rate at which costs are being incurred at time t as a result of pollution level p and decision r.

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[4] The mathematical derivation in this section is adapted to the pollution problem from the capital theory derivation of Dorfman.

[5] It is assumed that control over the pollutant is held exclusively by some decision-making body of a firm or society. For the purposes of exposition, the decision-making organization is referred to as the "firm."

[6] For ease of reading and typing, the time subscripts will be omitted except where necessary for clarity of presentation.

Thus, when $t = 0$, the total costs incurred between the initial date t_0 and some terminal date T, can be expressed by:

$$(2.1) \qquad C(p_0, \bar{r}) = \int_{t_0}^{T} c(p, r, t)\, dt$$

which is simply the sum of the rate at which costs are being incurred at every instant, discounted to the initial date, and added up for all instants. Note that the argument $c(t)$ accounts for the needed discounting. The variable $\bar{r}$ denotes the entire time path of the decision variable r from t_0 to T. This indicates that if the firm begins with initial pollution level p_0, then follows the removal policy $\bar{r}$, the resulting cost, C, is the integral of the costs incurred at each instant; these results in turn being dependent upon the time being considered, and the pollution stock and removal rate applicable at that time. The firm may choose the removal rate but cannot independently determine the pollution stock at each time. That stock is determined by the pollution stock at the initial time and the time path chosen for r. Thus, the rate of change of the pollution stock is determined by its present level, the time under consideration, and the removal rate. That is:

$$(2.2) \qquad \dot{p} = \frac{dp}{dt} = f(p, r, t).$$

The removal rate, then, at any given time, has two effects. It influences the rate at which costs are incurred at that time and it influences the rate at which the pollution stock changes, and thus, the level of pollution which will prevail in subsequent periods.

This is the essence of the dynamic decision-making process: to choose a time path (in this case $\bar{r}$) so as to optimize the integral of the stock variable (in this case to minimize the total pollution cost, C) taking into account the effect of the control variable on both the current costs and on the level of pollution in the future. The problem here, of course, is that the entire time path must be chosen, where standard calculus teaches us only how to derive a single optimal value of a variable. The solution is to transform this problem, which requires us to determine an entire time path, into one which requires us only to determine a single number. This solution is the maximum principle of optimal control theory, developed by L. S. Pontryagin and first presented by him in 1958.

Although the calculus of variations--which is a less generalized form of optimal control theory--dates back to the eighteenth century, its usefulness was severely limited by the requirement that the control variable must be the time rate of change of the state variable. This was only useful when the system being modeled was linear in the control variable, an uncommon occurrence in the real world. Pontryagin's contribution was to generalize the calculus of variations into a form in which more realistic non-linear models could be manipulated. Though written in general form, it is clear that the pollution problem would probably be non-linear in the control. It is intuitively reasonable to assume that the marginal removal cost of pollution will increase as the pollution level decreases. To remove one "unit" of pollutant at high pollution levels should be relatively easy compared with removing the same "unit" when pollution levels are low and the pollutant is scarce.

To derive Pontryagin's maximum principle, we first generalize the previous cost equation:

$$C(p_t,\vec{r},t)=\int_t^T c(p,r,t)\,dt. \tag{2.3}$$

Now consider two time intervals, a short time interval of length Δ beginning at time t and a longer interval from time $t+\Delta$ to time T. The short interval, Δ, may be thought of as being so short that the firm would not or could not change the removal rate. We can then split equation (2.3) into two intervals as follows:

$$C(p,\vec{r},t)=c(p_t,x_t,t)\Delta+\int_{t+\Delta}^T c[p(t+\Delta),r,t]\,dt. \tag{2.4}$$

This formula demonstrates that, given pollution stock p at time t, if the time path of removal is followed, the costs incurred to time T consist of two parts. The first is the rate at which costs are accrued during the interval times the length of the interval. The second is an integral in the same form as (2.3), except that it starts at time $t+\Delta$. Thus, we can rewrite (2.4) as:

$$C(p_t,\bar{r},t)=c(p,r_t,t)\Delta+C(p_{t+\Delta},\bar{r},t+\Delta). \tag{2.5}$$

If the firm knew the best choice of $\bar{r}$ from date t on, it could just follow that policy and obtain the optimal value of C, denoted V^* where:

$$V^*(p_t,t)=\min\ C(p_t,\bar{r},t). \tag{2.6}$$

V^* does not explicitly include the $\bar{r}$ argument as that argument has been optimized out. The minimum cost which can be obtained given p_t and t does not depend upon $\bar{r}$ but is the value which can be obtained from the best possible choice of $\bar{r}$.

Now assume that policy r_t is followed from t to $t+\Delta$, and that $\bar{r}$ is followed thereafter. The cost associated with such a circumstance would be:

$$V(p_t,r_t,t)=c(p_t,r_t,t)\Delta+V^*(p_{t+\Delta},t+\Delta). \tag{2.7}$$

That is, the costs accrued following such a policy are the costs from the initial period Δ under decision r_t, plus the minimum possible costs given time $t+\Delta$ and pollution $p(t+\Delta)$ resulting from the initial period. The equation has now been reduced to the ordinary problem of finding the optimal value of r_t. Once the optimal r_t is found and entered into the equation, V will be V^*.

To find the optimal value of r_t, we take the partial derivative of (2.7) with respect to r_t and set it equal to zero. We are assuming that this derivative does indeed give us a minimum rather than a maximum or an inflection point.

$$\frac{\partial V}{\partial r_t}=\Delta\frac{\partial}{\partial r_t}c(p,r_t,t)+\frac{\partial}{\partial r_t}V^*[p_{t+\Delta},t+\Delta]=0. \tag{2.8}$$

Although r_t is not explicit in the function V^*, it is implicit in the term $p_{t+\Delta}$. Thus the $\partial/\partial r_t\ V^*$ term may be rewritten as:

$$\text{(2.9)} \qquad \frac{\partial V^*}{\partial r_t} = \frac{\partial V^*}{\partial p(t+\Delta)} \frac{\partial p(t+\Delta)}{\partial r_t}$$

The first factor on the right hand side of equation (2.9) is the rate at which the minimized costs from time $t+\Delta$ change with respect to the pollution level existing at time $t+\Delta$. It may be considered to be the marginal damage cost of pollution at time $t+\Delta$, or the amount by which a unit increase in pollution level at time $t+\Delta$ would increase the minimum possible cost of pollution over time. Were pollution a "good" rather than a "bad" this would represent the marginal value of the capital stock, so it is represented at time t as $\lambda(t) = \frac{\partial}{\partial p} V^*(p,t)$. In the second factor, $p(t+\Delta)$ can be rewritten as $p(t) + \dot{p}\Delta$.

That is, the pollution level at time $t+\Delta$ is equal to the pollution level at time t plus the rate of change in pollution times the interval. From equation (2.2), $\dot{p} = f(p,r_t,t)$, we know that $\dot{p}$ depends upon r_t.

Thus, we can write $\frac{\partial}{r_t} p(t+\Delta) = \Delta \frac{\partial f}{\partial r_t}$. Substituting these two equations into (2.8), we get:

$$\text{(2.10)} \qquad \Delta\left(\frac{\partial c}{\partial r_t}\right) + \lambda(t+\Delta)\Delta\left(\frac{\partial f}{\partial r_t}\right) = 0.$$

We can approximate the term $\lambda(t+\Delta)$ as $\lambda(t) + \dot{\lambda}(t)\Delta$. That is, the marginal damage at $t+\Delta$ is the marginal damage at t plus the rate of change of λ times the interval over which it changes. Substituting this expression into equation (2.10), we get:

$$\text{(2.11)} \qquad \frac{\partial c}{\partial r_t} + \lambda(t)\frac{\partial f}{\partial r_t} + \dot{\lambda}(t)\Delta\frac{\partial f}{\partial r_t} = 0.$$

Now take the limit of equation (2.11) as $\Delta \to 0$. The third term approaches zero and the following equation results:

$$\frac{\partial c}{\partial r_t} + \lambda \frac{\partial f}{\partial r_t} = 0. \tag{2.12}$$

This is the first of the Pontryagin conditions and is well interpreted by Dorfman.

> It makes perfectly good sense to an economist. . . .that along the optimal path of the decision variable at any time, the marginal short-run effect of a change in decision must just counter-balance the effect of that decision on the total value of the capital stock an instant later. We see that because the second term in the equation is the marginal effect of the current decision on the rate of growth of capital with capital valued at its marginal worth, λ. The firm should choose [the control variable] at every moment so that the marginal immediate gain just equals the marginal long-run cost . . . . (p. 821).

Although Dorfman was speaking about capital in the more traditional sense, the analogy to our pollution problem is straightforward. In this case, the firm should choose a removal rate at every moment so that the discounted immediate marginal cost of removal is just equal to the discounted long-run marginal cost of leaving the pollution in the lake.

Now assume that the optimal r_t which satisfies equation (2.12) is obtained and that the firm initially establishes this as the removal rate. In this case, $V(p_t, r_t, t)$ becomes $V^*(p,t)$, and:

$$V^*(p,t) = c(p, r_t, t)\Delta + V^*[p(t+\Delta), t+\Delta]. \tag{2.13}$$

Differentiating this equation with respect to p, and remembering that the left hand side--by definition--equals $\lambda(t)$, results in:

$$\begin{aligned}\lambda(t) &= \Delta \frac{\partial c}{\partial p} + \frac{\partial}{\partial p} V^*[p(t+\Delta), t+\Delta] \\ &= \Delta \frac{\partial c}{\partial p} + \frac{\partial}{\partial p}[p(t+\Delta)]\,\lambda(t+\Delta) \\ &= \Delta \frac{\partial c}{\partial p} + \left(1 + \Delta \frac{\partial f}{\partial p}\right)(\lambda + \dot{\lambda}\Delta)\end{aligned}$$

$$= \Delta \frac{\partial c}{\partial p} + \lambda + \Delta\lambda\frac{\partial f}{\partial p} + \Delta\dot{\lambda} + \dot{\lambda}\frac{\partial f}{\partial p}\Delta^2$$

We can ignore the term in Δ^2 and make cancellations to obtain:[7]

(2.14) $$-\dot{\lambda} = \frac{\partial c}{\partial p} + \lambda\frac{\partial f}{\partial p}.$$

This is the second Pontryagin condition and--in a general sense--is the rate of change in the marginal value of capital. In a specific sense, it is the rate of depreciation of capital (depreciation vs. appreciation due to the negative sign of the $-\dot{\lambda}$ term). In our pollution example, this condition may be interpreted as the decrease in damage costs which would occur if a "unit" of pollution were postponed from entering the lake.

The Hamiltonian

Equations (2.12), (2.14), and (2.2) can be combined to create the Hamiltonian functional[8]:

(2.15) $$H = c(p,r,t) + \lambda(t)\, f(p,r,t).$$

This functional is the constrained dynamic optimization equation, analogous to the Lagrangian in static analysis. The Hamiltonian shows the total contribution to costs which occurs at an instant in time, taking into account all of the interrelationships we have discussed. Thus $H\Delta$ would be the total contribution to costs of all activities undertaken during period Δ. To minimize this cost, we take the partial derivatives of the Hamiltonian with respect to r, p, and λ, and set them equal to zero. In doing so, we are saying that we will, at every instant in time, choose that rate of removal which will minimize costs. If costs are minimized at every instant of time, total costs must also be at a minimum. Finally,

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[7] Since Δ is minute, Δ^2 must be even smaller and may be considered to be insignificant. This linearization is documented in Pontryagin, et al.

[8] The Hamiltonian is defined as a functional as the terms of the expression are functions rather than variables.

the derivatives of the Hamiltonian are equated to the previous results to create the formal Pontryagin conditions of optimal control. They are:

(2.16)
$$\frac{\partial H}{\partial r}=\frac{\partial c}{\partial r}+\lambda\frac{\partial f}{\partial r}=0$$

(2.17)
$$-\frac{\partial H}{\partial p}=\dot{\lambda}=\frac{\partial c}{\partial p}+\lambda\frac{\partial f}{\partial p}$$

(2.18)
$$\frac{\partial H}{\partial \lambda}=\dot{p}=f(p,r,t).$$

Note the reciprocal nature of the pollution level and the marginal cost of pollution in the equations. The partial derivative of H with respect to either is the time derivative of the other. Together, these three equations determine the time paths of $p(t)$, $r(t)$, and $\lambda(t)$. Condition (2.16), the maximum principle, indicates that the removal rate at every point in time should be chosen so that the marginal immediate costs just balance the value of the discounted marginal addition to the accumulated damage costs. That is to say, when the cost of removal equals the damage cost of the pollutant, the removal rate will be at an optimum. Condition (2.17), the adjoint equation, indicates that the pollution damage increases at the same rate that it adds to total costs. Condition (2.18), the equation of motion, shows how the pollution level changes as a result of its current level and the decisions made. These three equations may be manipulated, by substitution, into two equations in the form of time derivatives. Given boundary conditions, the two-equation system can be solved for the decision variable at a given time. This process may be repeated to obtain the optimal values of the decision variable through the entire time path.

The boundary conditions may either be initial conditions, which describe the pollution level at time $t=0$, or terminal conditions, which describe the target pollution level at $t=T$. For example, we may know the current level of pollution in our lake and we may set a target that at finite time T, the pollution level should equal zero. We could then trace the entire time path of the removal rate necessary to achieve the terminal condition given the initial condition.

While this derivation defines only a single actor with a single goal and control variable, the optimal control methodology may be generalized to multiple states, controls, and goals. The model developed in this study includes a single state variable, two control variables and four goals with two actors. The concept of multiple goals is discussed in the last section of this chapter.

Multiple Policymaker Goals

With one exception, each of the models reviewed in this chapter has assumed a single objective on the part of each actor represented. Van Kooten, et al., however, developed a model specifically to examine the trade-off between net returns and soil quality for farmers in southwestern Saskatchewan. These competing goals must be balanced by the farmer according to some personal preference function. Various weights were assigned to each objective and a trade-off function was derived to examine the relationship between the goals.

Even more than the producer, a policymaker must balance many competing goals in policy implementation. The policymaker is influenced in specific implementation decisions by political pressures, social welfare, and his own preference function. Reichelderfer and Boggess state that the correct specification of program decision makers' objectives is critical. Rausser (1981) attempted to achieve this by specifying a weighted political preference function. The model incorporated a weighting scheme to represent the relative importance of the various objectives of an agricultural policymaker. In a similar manner, Sylvia and Anderson applied weights to various policy goals in a dynamic model of net-pen aquaculture. The relative values of the weights were then allowed to vary, providing a set of policy frontiers over time.

These three elements of a soil erosion policy model--the interaction of the producer and policymaker, the dynamic representation of the sedimentation process, and the explicit specification of multiple policy goals--are incorporated into the model described in detail in Chapter III.

CHAPTER III

THE THEORETICAL MODEL

THE PRODUCER'S DYNAMIC MODEL

The farmer produces crops and erosion as he seeks to maximize the time stream of discounted profits. The use of profit maximization as the objective of producers is well established in economic theory (Henderson and Quandt; Van Kooten, et al.). The erosion results from tillage of the soil for planting and from harvesting. Erosion production is measured as some multiple of production and the stock of eroded soil (hereafter referred to as erosion stock) is eliminated through runoff into streams and ditches carried by rain. The erosion affects the productivity of the farm production and negatively impacts waterways downstream in the form of sediment. While potential instruments for controlling erosion by the farmer might include controls such as tillage practices, site placement, field size and field slope, it is assumed that such factors are fixed and that the only existing instrument is production. Variations in the other factors are assumed to be accounted for in the cost equation. The only instrument available to the policymaker to affect the farmer's decisions is a per unit "tax" on erosion. The "producer" in this model is assumed to be a homogeneous aggregation of all individual producers within the producing area.

The producer's formal problem is:

(3.1) $$\text{Maximize} \int_{t=0}^{T=\infty} e^{-rt}[pY(t) - C(Y(t)) - \tau E(t)]\,dt$$

(3.2) $$\text{subject to: } \dot{E} = F(E(t), Y(t)),$$

and the usual set of non-negativity and convexity conditions, where: p is the revenue per unit of production, Y is the number of units produced, C is a convex production cost function, τ is a per unit erosion tax, E is the erosion stock, t is time, r is the private instantaneous annual rate of discount, and F represents the erosion state equation.

Using an optimal control framework, the current-value Hamiltonian is:

(3.3) $$H^{cv} = [pY(t) - C(Y(t)) - \tau E(t)] + \lambda F(E(t), Y(t)).$$

The necessary conditions are:

(3.4) $$\frac{\partial H}{\partial Y} = (p - C'(Y)) + \lambda F'(Y) = 0$$ (optimality condition)

(3.5) $$-\frac{\partial H}{\partial E} = \dot{\lambda} - r\lambda = \tau - \lambda F'(E)$$ (adjoint equation)

(3.6) $$\frac{\partial H}{\partial \lambda} = F(E, Y) = \dot{E}$$ (equation of motion).

The optimality condition indicates that the short-run profits must just equal the incremental erosion costs to the farmer. The adjoint equation relates the change in the marginal cost of erosion to the tax rate, the private rate of discount, and the erosion stock. The equation of motion indicates that the physical/economic optimum must equate the production and natural decay of erosion. It is implicitly assumed that the transversality and complementary slackness conditions hold as follows: $\lambda(T) \geq 0$ and $\lambda(T)E(T) = 0$.

The Pontryagin conditions can be manipulated into a dynamic plane equation system of two first-order differential equations in $\dot{Y}$ and $\dot{E}$.

Rearranging (3.4) to isolate λ yields

(3.7) $$\lambda = \frac{C'(Y) - p}{F'(Y)}$$

then taking the derivative of (3.7) with respect to time yields

(3.8) $$\dot{\lambda} = \dot{Y}[(C''(Y))(F'(Y))^{-1} - (C'(Y)-p)(F'(Y))^{-2}(F''(Y))].$$

Rearranging (3.5) to isolate $\dot{\lambda}$, yields

(3.9) $$\dot{\lambda} = \lambda(r - F'(E)) + \tau,$$

then equation (3.7) is substituted into (3.9), resulting in a function of Y and E only:

(3.10) $$\dot{\lambda} = \frac{C'(Y)-p}{F'(Y)}(r-F'(E)) + \tau.$$

The first and second conditions are combined, and all λ terms are eliminated by equating (3.8) and (3.10), giving

(3.11) $$\dot{Y}\left[\frac{C''(Y)}{F'(Y)} - \frac{(C'(Y)-p)(F''(Y))}{(F'(Y))^2}\right] = \frac{(C'(Y)-p)}{F'(Y)}(r-F'(E)) + \tau.$$

Rearranging (3.11) yields the differential expression for the optimal change in output:

(3.12) $$\dot{Y} = \frac{(C'(Y)-p)(r-F'(E))(F'(Y)) + \tau(F'(Y))^2}{(C''(Y))(F'(Y)) - (C'(Y)-p)(F''(Y))}.$$

The state equation, showing the change in the erosion stock over time, may be represented by the explicit equation:

(3.13) $$F(E(t),Y(t)) = \dot{E} = -hE(t) + kY(t), \text{ subject to } 0<h,k<1,$$

where h is the coefficient of decay of the erosion stock and k is the erosion production coefficient. Thus, the net change in erosion stock in a given period of time is the erosion generated from production less the eroded soil carried out of the study area by the action of wind or water.

The producer's cost function is assumed to take the form:

(3.14) $$C(Y(t)) = q + dY(t) + gY^2(t), \text{ subject to } q\geq 0;\ d,g>0.$$

This form is consistent with microeconomic theory and previous empirical analysis (Ervin, et al.; Henderson and Quandt; Sylvia and Anderson).

Substituting equations (3.13) and (3.14) into (3.1) and solving the partial derivatives for the explicit form of (3.12) yields:

$$\dot{Y} = Y(r+h) + \frac{(d-p)(r+h) + \tau k}{2g}. \qquad (3.15)$$

Equations (3.13) and (3.15) constitute our system of first-order differential equations. To evaluate the motion of this system, we must first identify those locations in which the system is stable, that is, the steady states associated with these equations. At equilibrium, the change in Y over time, $\dot{Y}$, becomes zero. Thus, setting equation (3.15) equal to zero and solving for Y will result in the equilibrium level of output, Y^*:

$$Y^* = \frac{(p-d)}{2g} - \frac{\tau k}{2g(r+h)}. \qquad (3.16)$$

The equation of motion (3.6) will also be zero at steady state. By substituting (3.16) into (3.6) and setting it equal to zero, the equilibrium erosion stock, E^*, may be found:

$$E^* = \frac{k}{h}Y^* = \frac{k(p-d)}{2gh} - \frac{\tau k^2}{2gh(r+h)}. \qquad (3.17)$$

Each isocline in Figure 3.1 shows the schedule of points on which its respective variable will not change, and the intersection of those lines--at Y^*, E^*--shows the only equilibrium point which exists in this system. At Y^*, E^*, neither the acreage in production nor the erosion rate would change. Since it is presumed that the system is not at equilibrium, we are particularly interested in the stability of the equilibrium and the motion which takes place elsewhere in the plane. We can determine that motion, and the nature of the steady state, with equations (3.13) and (3.15). We take the derivative of each with respect to Y,[9] and determine the sign of the result:

$$\frac{\partial \dot{Y}}{\partial Y} = r + h \quad > 0, \tag{3.18}$$

$$\frac{\partial \dot{E}}{\partial Y} = k \quad > 0, \tag{3.19}$$

and plot the motion which occurs around the steady state.

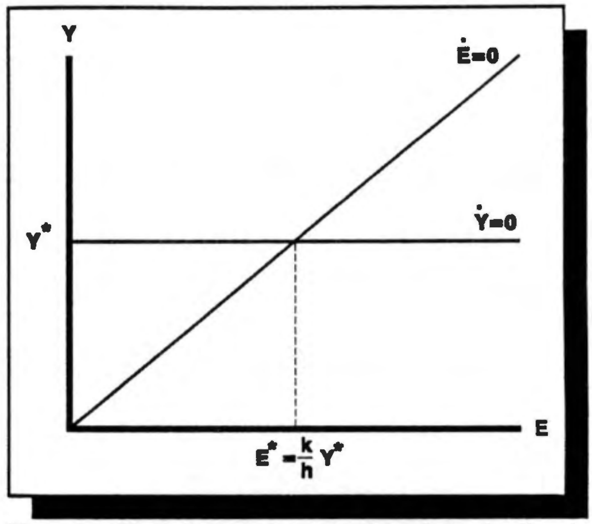

Figure 3.1. Phase diagram demonstrating solution isoclines in Y, E space.

Figure 3.2 shows the effect of a movement off of the isoclines. From (3.18) we know that any movement off of $\dot{Y}=0$ will result in further movement in the same direction. Therefore, the equilibrium is unstable with respect to *Y*. Equation (3.19) shows that any positive (upward) movement of *Y* from $\dot{E}=0$ will result in a positive (rightward) movement in *E*. If we think of the two isoclines as dividing the plane into four quadrants as shown in Figure 3.2, the trajectories within each quadrant will move as in Figure 3.3. The movement clearly defines a saddle-point equilibrium. Although there are an infinite number of trajectories that satisfy the differential equation system, there is only one line which converges directly to the equilibrium and only

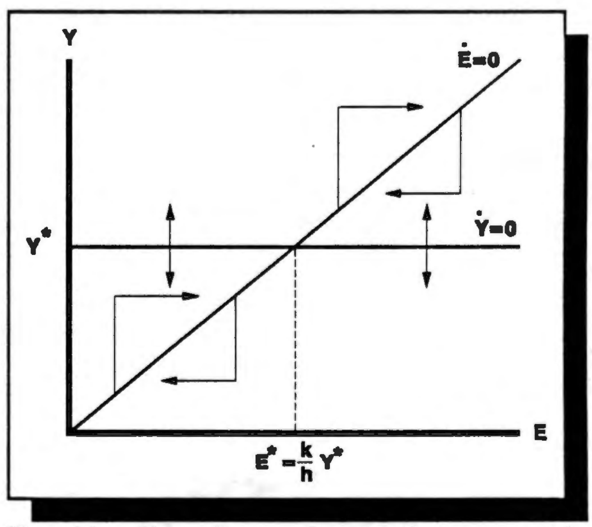

Figure 3.2. Phase diagram demonstrating movement by quadrant.

[9]Normally, the derivative of each would be taken with respect to the other as that usually gives a more tractable result. This system is unusual, however, in that $\dot{Y}$ is not a function E. The necessary information is still obtained by taking the derivative of $\dot{Y}$ with respect to Y, although the result is somewhat more difficult to interpret.

one line which diverges directly from the equilibrium. These lines, the convergent and divergent separatrices respectively, will not be crossed by any trajectory and therefore provide a boundary of movement for all of the trajectories. All trajectories other than the separatrices will miss the steady state point and will either pass into another quadrant or out of the relevant range of the diagram. The trajectory that crosses a quadrant boundary takes on the attributes of the new quadrant.

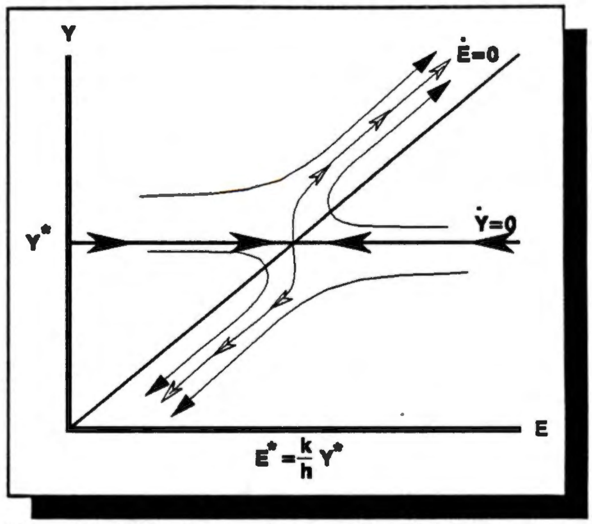

Figure 3.3. Phase diagram demonstrating global movement of trajectories.

In order to meet the transversality conditions, where $T=\infty$, the producer must approach the equilibrium at Y^*, E^* as $t\to\infty$. Since point A is a saddle-point, the only approach path is along the convergent separatrix where $\dot{Y}=0$. The producer's profit maximizing strategy is to adjust output to Y^*. Erosion stock will then either increase or decrease toward equilibrium at E^*, depending upon whether the initial condition of E is to the right or to the left of $\dot{E}=0$.

THE POLICYMAKER'S DYNAMIC MODEL

Once the optimal producer's behavior is determined, the policymaker's dynamic problem may be solved. Assume that the policymaker wishes to maximize the stream of discounted net revenue from agricultural production, water quality, and taxes on erosion. The producer may use the producer response information derived from the producer's model to determine the optimal tax policy. The policymaker's formal problem is:

(3.20) $$\text{Maximize} \int_{t=0}^{T=\infty} e^{-\delta t}[apY(t) - b\gamma E(t) + c\tau(t)E(t)]\, dt$$

(3.21) subject to: $\dot{E}=F(E(t),Y(t))$

(3.22) $\dot{Y}=G(Y(t),\tau(t))$

$$a+b+c=1;\ 0\leq a,b<1;\ 0<c\leq 1;$$

and the usual set of non-negativity and convexity conditions where:

a, b, c = the relative weights the policymaker attaches to agricultural revenue, water quality, and tax revenue, respectively;

G = the state equation for Y resulting from the producer's movement along the optimal path;

γ = the unit cost of the erosion stock, E ; and

δ = the social instantaneous annual rate of discount.

The $pY(t)$ term is the increase in the value of the objective functional due to agricultural production, $-\gamma E(t)$ is the decrease in the value of the objective functional due to erosion damages, and $\tau(t)E(t)$ is the increase in the value of the objective functional due to tax revenues.

The current value Hamiltonian for the problem is:

(3.23) $$H^{cv}=apY(t)-b\gamma E(t)+c\tau(t)E(t)+\mu[F(E(t),Y(t))]$$

The condition expressed in equation (3.22) does not appear in the Hamiltonian. In the producer model, the producer's optimal path was to move production to Y^* and continue to perpetually produce at that level. Thus $\dot{Y}=0$.

Substituting (3.13) into (3.23) yields the explicit Hamiltonian:

(3.24) $$H=apY-b\gamma E+c\tau E+\mu[-hE+kY].$$

Since the producer's optimal production is at Y^*, given some tax rate, Y^* from (3.16) is substituted for Y in (3.24):

(3.25) $$H=ap\left[\frac{p-d}{2g}-\frac{\tau k}{2g(r+h)}\right]-b\gamma E+c\tau E+\mu\left[-hE+k\left(\frac{p-d}{2g}-\frac{\tau k}{2g(r+h)}\right)\right].$$

The necessary conditions are:

(3.26)
$$\frac{\partial H}{\partial \tau} = -\frac{apk}{2g(r+h)} + cE - \frac{\mu k^2}{2g(r+h)} = 0$$

(3.27)
$$-\frac{\partial H}{\partial E} = b\gamma - c\tau + \mu h = \dot{\mu} - \delta\mu$$

(3.28)
$$\frac{\partial H}{\partial \mu} = \dot{E} = -hE + k\left[\frac{p-d}{2g} - \frac{\tau k}{2g(r+h)}\right].$$

Rearranging (3.26) yields:

(3.29)
$$\frac{\mu k^2}{2g(r+h)} = cE - \frac{apk}{2g(r+h)}.$$

An examination of the Hamiltonian demonstrates that the system is linear in the control. Thus, by Miller, the solution is of the "bang-bang" type and the following tax rates derived from (3.29) would prove optimal:

$$\text{If } \frac{apk}{2g(r+h)} - cE \begin{cases} > \dfrac{\mu k^2}{2g(r+h)} & \text{then } \tau^{min} \\ = \dfrac{\mu k^2}{2g(r+h)} & \text{then } \tau^{*} \\ < \dfrac{\mu k^2}{2g(r+h)} & \text{then } \tau^{max} \end{cases}$$

The interpretation of this solution is straightforward. $\frac{apk}{2g(r+h)}$ is the amount by which agricultural revenues are decreased in the current period, cE is the amount by which tax revenues are increased in the current period, and $\frac{\mu k^2}{2g(r+h)}$ is the amount by which the discounted stream of future erosion damage decreases, all when the tax rate is increased by one unit. Thus, when $\frac{apk}{2g(r+h)} - cE > \frac{\mu k^2}{2g(r+h)}$, the value of agricultural production and tax revenue is more valuable to the policymaker than the cost of erosion damage resulting from production. Given this, the policymaker wants to increase production to Y^* and he implements tax rate τ^{min}. When $\frac{apk}{2g(r+h)} - cE < \frac{\mu k^2}{2g(r+h)}$, the policymaker values clean water more highly than current production and he implements tax rate τ^{max} to decrease agricultural erosion.

The Pontryagin conditions can be manipulated to yield the optimal tax rate, τ^*. From (3.29), isolate μ:

(3.30) $$\mu = \frac{2cgE(r+h) - apk}{k^2}.$$

Then take the time derivative of μ in (3.30):

(3.31) $$\frac{\partial \mu}{\partial t} = \frac{2cg(r+h)}{k^2}\dot{E}.$$

Similarly, equation (3.27) can be arranged to isolate $\dot{\mu}$:

(3.32) $$\dot{\mu} = b\gamma - c\tau + \mu(h+\delta).$$

Eliminating $\dot{\mu}$ by setting (3.31) and (3.32) equal yields:

(3.33) $$\frac{2cg(r+h)}{k^2}\dot{E} = b\gamma - c\tau + \mu(h+\delta).$$

All elements of the necessary conditions are now included in the equation as $\dot{E}$ from (3.28) and μ from (3.30) are substituted into (3.33):

(3.34) $$\frac{2cg(r+h)}{k^2}\left[-hE+k\left(\frac{p-d}{2g}-\frac{\tau k}{2g(r+h)}\right)\right]=b\gamma-c\tau+(h+\delta)\left[\frac{2cgE(r+h)-apk}{k^2}\right].$$

All τ terms are isolated on the left side of the equation:

(3.35) $$c\tau-\frac{2cg(r+h)}{k^2}\frac{k^2}{2g(r+h)}\tau=\frac{2cgh(r+h)}{k^2}E+\frac{2cg(h+\delta)(r+h)}{k^2}E-\frac{2cgk(r+h)(p-d)}{2gk^2}+b\gamma-\frac{apk(h+\delta)}{k^2}.$$

Equation (3.35), when simplified, results in the equality:

(3.36) $$0=\left[\frac{2cgh(r+h)+2cg(h+\delta)(r+h)}{k^2}\right]E-\frac{c(r+h)(p-d)}{k}+b\gamma-\frac{ap(h+\delta)}{k}.$$

Although there is no longer an explicit τ term, τ is implicit in the optimal level of E. To isolate the implicit τ, the E term is moved to the left hand side, and the entire equation is multiplied by $-k^2$:

(3.37) $$E[2cgh(r+h)+2cg(h+\delta)(r+h)]=ck(r+h)(p-d)+apk(h+\delta)-b\gamma k^2.$$

To obtain the optimal tax rate, τ^*, the optimal erosion stock, E^*, from the producer model (3.17) is substituted into (3.37):

(3.38) $$\left[\frac{k(p-d)}{2gh}-\frac{\tau k^2}{2gh(r+h)}\right][2cgh(r+h)+2cg(h+\delta)(r+h)]=ck(r+h)(p-d)+apk(h+\delta)-b\gamma k^2,$$

and the equation is rearranged to isolate τ^*:

(3.39) $$\frac{\tau k^2}{h}[c(2h+\delta)]=\frac{k(p-d)}{h}[c(r+h)(2h+\delta)]-ck(r+h)(p-d)-apk(h+\delta)+b\gamma k^2,$$

(3.40) $$\tau^*=\frac{hk(p-d)[c(r+h)(2h+\delta)]}{hk^2[c(2h+\delta)]}-\frac{chk(r+h)(p-d)}{k^2[c(2h+\delta)]}-\frac{aphk(h+\delta)}{k^2[c(2h+\delta)]}+\frac{b\gamma hk^2}{k^2[c(2h+\delta)]},$$

and simplified:

$$\tau^* = \frac{(h+\delta)(p-d)(r+h)}{k(2h+\delta)} - \frac{aph(h+\delta)}{kc(2h+\delta)} + \frac{b\gamma h}{c(2h+\delta)}. \tag{3.41}$$

The optimal tax rate equation can be thought of as a tax response function of the policymaker's, or society's, values of agricultural production versus water quality. A greater value placed on agricultural revenues (a) by the policymaker results in a lower the equilibrium tax rate. Conversely, a greater value placed on water quality (b) results in a higher equilibrium tax rate. The relationship between the value for tax revenues (c) and the tax rate, however, depends upon the elasticity of the tax revenue supply curve which is determined by the relative values of *h* and *k* (Sylvia and Anderson).

CHAPTER IV

THE EMPIRICAL MODEL

A theoretical model may be useful in describing an economic process, but validation of the model through empirical application allows the researcher to analyze the ability of the model to accurately reflect events in the real world. An econometric model readily lends itself to statistical hypothesis testing, yet a mathematical model requires other means of validation. In such a case, judgement on the validity of a model may be based upon the weight of evidence, through application, rather than through statistical inference (Tweeten). The empirical application of the model developed in Chapter III will allow both for non-statistical validation of the model and for development of further insights into the relationships being modeled.

STUDY AREA

To this point, no mention has been made of a geographical site for the model. This is because the model itself is not site specific. The expectation is that the model would be applied to specific crops in hydrologically homogeneous regions at the watershed level. In this way, the optimal tax level would vary according the specific characteristics of a region and the crops grown therein. This also allows the flexibility to assign differing levels of priority to agricultural production versus environmental quality based upon specific socio-economic criteria. Agriculture may well be given higher priority in prime agricultural areas while surface water quality may be more highly weighted in areas that are environmentally sensitive.

There are several characteristics which must be possessed by the study area. First, the area must support significant agricultural production. Second, the area must be subject to significant agricultural erosion. Finally, there must be sufficient information available on the area to develop the data required by the model. Such information includes land use, agricultural production practices, agricultural production costs, soil characteristics, hydrology, and offsite erosion damage costs. Several sites in Tennessee meet the first two criteria, but the third requirement is more difficult to accommodate.

From those watersheds that meet the first two criteria, a three-county region in northwestern Tennessee is selected. The selected study area includes Obion, Weakley and Gibson Counties (Figure 4.1). The study area meets the first criterion in that it is predominantly agricultural, with a majority of its land area being engaged in agriculture. The second criterion is also met. West Tennessee has the highest average erosion rate in the nation (Moore and Klaine). Finally, a study on groundwater contamination was recently completed in the area which provides much of the information needed for the application of this model (Cole). Thus, all three criteria are fully met in this area.

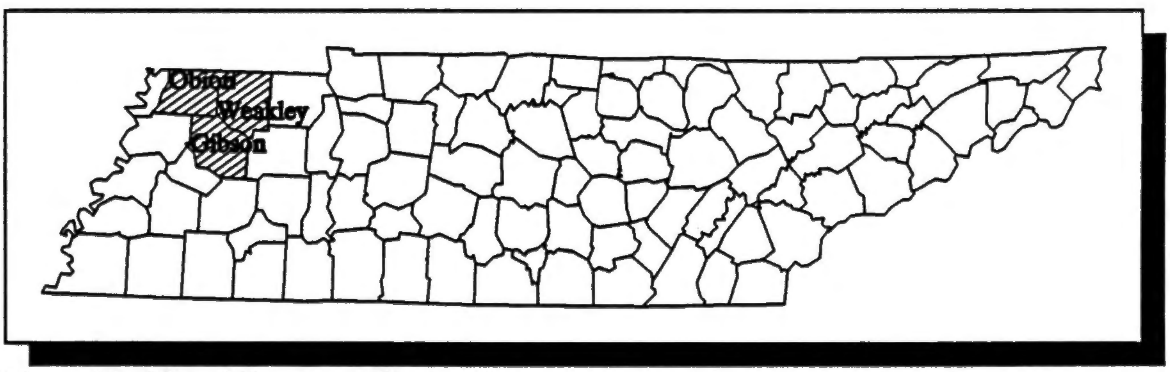

Figure 4.1. Map of Tennessee, showing the study area.

Description of Study Area

The three selected counties are located in the area categorized by the Soil Conservation Service as the Southern Mississippi Valley Silty Uplands, or Major Land Resource Area 134 (USDA/SCS, 1981). The region is also referred to as the Southern Plateau Slope (Mundy and Gray). With elevations ranging from 25 to 100 meters (USDA/SCS, 1981), this region lies between the Mississippi bottomlands and the Cumberland Plateau.

The majority of the land in the area is used for agriculture, with corn, soybeans and wheat being the primary crops. Given their predominance in the region, each of these commodities is modeled separately in this analysis. Agricultural practices and production enterprises are consistent throughout the three counties (Mundy and Gray), as are the hydrological characteristics (Water Resources Council). Precipitation is abundant in the area, averaging about 50 inches per year, and yields of major crops are above state averages (Mundy and Gray).

There are 12 primary soil types in the watershed. The soils are mainly from deep or moderately deep loess with Loring, Falaya and Collins accounting for more than 50% of the total cropland area. The soil types of the region are listed in Table 4.1. The area is largely rural, with only 42% of the population being classified as urban. The largest incorporated city in the area has a population of less than 11,000. Selected demographics of the area are presented in Figure 4.2.

Table 4.1. Acreage distribution by soil type.

Soil Type	Acreage	Percentage
Adler	8,881	1.9
Birds	5,609	1.2
Calloway	38,327	8.2
Collins	59,360	12.7
Convent	3,739	0.8
Falaya	79,991	16.9
Grenada	73,382	15.7
Lexington	7,011	1.5
Loring	108,903	23.3
Memphis	28,511	6.1
Providence	18,229	3.9
Waverly	36,457	7.8
Total	467,400	100.0

Source: Cole, 1991

Data Needs

Data required for a numerical solution to the model include several economic and physical coefficients, most of which are not readily available for a given watershed. Because many of these coefficients are crop-specific, the model is best applied to each crop individually. Ultimately, the

OBION COUNTY		
Area (square miles):	550	
Population per Square Mile:	60	
Population		
Urban:	13,171	(40.2%)
Rural:	19,610	(59.8%)
Population of Incorporated Cities		
South Fulton:	2,375	
Union City:	10,436	
WEAKLEY COUNTY		
Area (square miles):	581	
Population per Square Mile:	57	
Population		
Urban:	14,394	(39.5%)
Rural:	23,766	(60.5%)
Population of Incorporated Cities		
McKenzie:	5,405	
Martin:	8,989	
GIBSON COUNTY		
Area (square miles):	602	
Population per Square Mile:	82	
Population		
Urban:	22,893	(46.3%)
Rural:	26,574	(53.7%)
Population of Incorporated Cities		
Humboldt:	10,290	
Milan:	8,083	
Trenton:	4,601	

Source: Tennessee Statistical Abstracts, 1989

Figure 4.2. Demographics of the study area.

analytical model is reduced to two key equations which represent the decisions made by the producer and the policymaker. The final policymaker decision is reflected in equation 3.41 from Chapter III:

$$(3.41) \qquad \tau^* = \frac{(h+\delta)(p-d)(r+h)}{k(2h+\delta)} - \frac{aph(h+\delta)}{kc(2h+\delta)} + \frac{b\gamma h}{c(2h+\delta)},$$

where τ^* is the optimal tax rate; and d and g are the linear and quadratic terms of the cost equation:

$$(3.14) \qquad C(Y(t)) = q + dY(t) + gY^2(t), \text{ subject to } q \geq 0;\ d, g > 0.$$

Variables h and k are the sediment decay and growth coefficients, respectively, of the equation of motion:

$$(3.13) \qquad F(E(t), Y(t)) = \dot{E} = -hE(t) + kY(t), \text{ subject to } 0 < h, k < 1.$$

Variables r and δ are the private and social discount rates, respectively; p is the unit price of the commodity; γ is the unit cost to society of offsite sediment damage; and a, b and c are the relative weights society places on agriculture, the environment, and tax revenues respectively.

The final producer decision is defined as:

$$(3.16) \qquad Y^* = \frac{(p-d)}{2g} - \frac{\tau k}{2g(r+h)},$$

where Y^* is the optimal level of production; τ is the applicable tax rate; and d, g, h, k, r and p are as defined above.

Economic Coefficients

The economic data required include the cost equation, the commodity price, the unit cost of offsite sediment damages and the private and social discount rates. A review of literature reveals no previous studies in which agricultural production cost equations are derived for the study area. Thus, it is necessary to estimate cost equations from available data. A combined linear programming/linear regression model is developed to estimate these equations. The development of this model is described in detail in the Data Modeling section of this chapter.

The proxy used in this study for the real social instantaneous annual rate of discount is the nominal rate on AAA corporate bonds for June 1987 less the percentage change in price from June 1986-1987 (Federal Reserve Board). This rate, $\delta = 0.05$, is assumed to be a good average of the productivity of low-risk investments in the capital markets. The assumed private instantaneous annual rate of discount is based upon the annual long-term fixed deposit rates offered by commercial banks in the area. The private discount rate of $r = 0.10$ is the median of rates quoted by several banks operating in Memphis, Tennessee.

The unit cost of offsite sediment damages is drawn from Alexander and English which identifies offsite sediment damage costs for watersheds across the United States. In this paper, the authors used an interregional sedimentation model to estimate the impact of the Conservation Reserve Program on sedimentation and on the offsite costs of sediment damage. The authors combined the offsite erosion damage costs reported by Clark, et al. and the erosion levels reported in the 1982 National Resources Inventory (NRI) to provide a base from which cost per ton estimates are generated. Erosion data are taken from the NRI, aggregated to a producing area level, and multiplied by appropriate sediment delivery ratios. The resulting estimates of suspended and deposited sediment are aggregated into regional estimates, and the total sediment costs are divided by this result. The unit cost of offsite sediment damages for this area is $6.38 per ton.

The price of each commodity is obtained from *Tennessee Agriculture, 1990* (Tennessee Department of Agriculture), reflecting 1988 values. The 1988 values are used to maintain consistency with the cost figures. Other methods of setting prices are possible, such as attempting to forecast an average future price, but such methods have frequently been shown to be no better than naive forecasts (Pindyck and Rubenfeld). In this model, since price is held constant, consistency with costs is chosen as the more important attribute of the price levels with the understanding that this introduces the implicit assumption that producers expect these price levels perpetually. The prices used are: $2.75 per bushel for corn, $7.65 per bushel for soybeans, and $3.40 per bushel for wheat.

Physical Coefficients

The physical data required are the coefficients of the equation of motion: the sediment growth coefficient and the sediment decay coefficient. The sediment growth coefficient is developed using the Erosion Productivity Impact Calculator (EPIC), a plant growth/erosion simulator. The development of this model is described in detail in the Data Modeling section of this chapter.

The sediment decay coefficient is much more difficult to estimate than the sediment growth coefficient. A literature search revealed no information on studies in which sediment movement as defined in this model have been measured. Discussions with Dr. Don Myer[10] served largely to confirm the difficulty in estimating such a figure. Some generalizations can be made, however. One is that sediment decay as described in this model can be expected to be extremely slow. Further, the level of sediment decay will be very minor as compared with new sediment contained in both agricultural and non-agricultural runoff. While this decay could vary between 0 and 25 percent annually, depending upon the specific hydrology of an area, most values will fall in the lower extreme of the range. An estimate of .01 is selected for this coefficient. This estimate, while somewhat arbitrary, is consistent with the available knowledge at this time.

DATA MODELING

The Cost Equation

The development of a cost equation for this watershed presents the modeler with the same task facing producers, which is determining an efficient allocation of limited resource inputs among competing alternatives. In both cases, the intent is to minimize the cost associated with production of

[10]Personal communication with Dr. Don Myer, USDA National Sedimentation Laboratory, Oxford Mississippi, 1991.

a given level of output.[11] The modeling task is complicated further in that the cost equation must account for all of the resources of the region and it must reflect the change in costs as output changes.

Linear programming is a mathematical method commonly used to analyze the problem of efficiently allocating limited resources among competing agricultural production enterprises (Hillier and Lieberman). The linear programming algorithm may be used to determine the minimum cost required to produce a given output subject to the constraints imposed by the physical processes. Such a cost-minimizing model is used in this study to generate individual points on a cost curve. Each of the 12 soil types is associated with a cost of production and a yield potential. The model selects those combinations which meet the exogenously specified revenue constraint at the least cost. Once the basic model is developed, it is run multiple times using an increasing revenue requirement in each run. Revenue is chosen, rather than yield, to standardize the model across different crops. For each crop, the model is run with revenue constrained to a minimum of five million dollars, with subsequent constraints increasing at five million dollar increments until an infeasible solution is obtained. The resulting minimum cost levels are then associated with the corresponding levels of output, through linear regression, to obtain continuous equations representing the relationship between cost and output.

The linear programming model may be mathematically expressed as:

$$(4.1) \quad \text{MIN} \quad Z = CX$$

$$\text{s.t.} \quad IX \leq L, \quad DX \geq R, \quad X \geq 0; \text{ for all } x$$

where: Z is the scalar objective function value, total cost;

X is a 12×1 vector of production activities by soil type;

C is a 1×12 vector of activity costs;

I is a 12×12 identity matrix;

[11]A producer's goal is generally expressed as profit maximization which is the dual formulation of cost minimization. On optimization, the results of each are equivalent, so the producer's behavior may be expressed in either form (Henderson and Quandt).

L is a 12×1 vector of land resources available by soil type;

D is a 1×12 vector of receipts per acre by activity; and

R is a scalar representing total revenue.

The model is run for each major commodity in the area--corn, soybeans and wheat--assuming homogeneous production of the commodity being modeled in each run. These three commodities represent over 70 percent of the agricultural production of the area (Mundy and Gray).

One problem involved in modeling an entire watershed is the variation in tillage practices. Practices vary from one farmer to another and over time. To account for this while still maintaining a parsimonious model, each commodity model is run under two different tillage conditions: conventional tillage and conservation tillage. This creates a bound on the results and allows for an analysis of the sensitivity of the results to tillage practices.

Six models result from the system explained above and are referred to in this study as the primary model configurations. Specifically, the primary model configurations are: conventional tillage corn; conservation tillage corn; conventional tillage soybeans; conservation tillage soybeans; conventional tillage wheat; and conservation tillage wheat. The linear programming model input files for each of the primary model configurations, written in the General Algebraic Modeling System (GAMS) language, are shown in Appendix A. The models shown in the appendix are the first run for each primary configuration option with the revenue constraint set at five million dollars. Upon completion of the modeling runs, the optimal cost results are regressed against the output levels and the output levels squared using multivariate no-intercept ordinary least squares. The model is run with no intercept as the intercept term is not used in any of the final equations. Eastwood, et al. point out that this may increase the value of R^2, but in the use of regression to derive a continuous function from artificially-generated data, the R^2 values are not of critical importance. All coefficients derived from the regression are significant at a .95 or .90 level of confidence, except the quadratic term of the conservation tillage wheat model. Table 4.2 shows the results of the regression. The Y and Y^2 terms in the regression correspond to the d and g terms in the optimal control model respectively.

Table 4.2. Regression results of cost equation estimation.

	Corn		Soybeans		Wheat	
	Conventional	No-Till	Conventional	No-Till	Conventional	No-Till
Constant†	0	0	0	0	0	0
Std $Error_{Reg}$	216557.2	702081.9	271129.8	375038.7	684555.5	815650.2
R^2	.99	.99	.99	.99	.99	.99
Observations	30	30	28	28	15	15
Deg. of Freedom	28	28	26	26	13	13
Y Coefficient (t-value)	1.144436 (233.42)	1.242335 (77.71)	2.61985 (137.40)	2.855822 (107.65)	2.839073 (44.22)	3.214053 (41.92)
Y^2 Coefficient (t-value)	4.7×10^{-9} (41.01)	5.5×10^{-9} (14.81)	3.1×10^{-8} (23.65)	3.6×10^{-8} (19.56)	8.8×10^{-9} (1.90)	5.7×10^{-9} (1.03)

†As the constant does not appear in the final equations, it was forced to zero in the regression.

The Sediment Growth Coefficient

Development of the sediment growth coefficients (Table 4.3) requires information on the production practices being employed, the yields being received under those practices, and the erosion resulting from those practices. While information exists on the actual erosion levels occurring on some lands in the study area, simulated erosion levels based upon the assumptions of the linear programming model are deemed to best maintain the consistency of the modeling system. The estimation of erosion under the model conditions requires a plant growth/erosion simulator.

Existing simulators appear to offer the option of plant-specific models or more general models. A general model is selected for use in this study to maintain consistency in assumptions and modeling techniques across different crop simulations. The selection criteria for the plant growth/erosion simulator include:

1. the ability to incorporate different tillage practices;
2. the ability to incorporate a variety of crop types; and
3. the ability to model soil movement for a wide variety of soil types and slopes.

Table 4.3. Development of the sediment growth coefficient.

Coefficient	Corn		Soybeans		Wheat	
	Conv Till[†]	Cons Till[‡]	Conv Till	Cons Till	Conv Till	Cons Till
Erosion (tons/acre)	20.06	16.09	21.20	16.68	7.33	5.34
Sediment Delivery Ratio	.35	.35	.35	.35	.35	.35
Sedimentation (tons/acre)	7.02	5.63	7.42	5.84	2.57	2.57
Average Yield (bushels/acre)	120.50	115.35	38.51	38.36	49.45	49.80
Sediment Growth Coefficient (tons/bushel)	.0583	.0488	.1926	.1522	.0519	.0376

[†]Conventional Tillage
[‡]Conservation Tillage

Based on the above criteria, the EPIC model is used as the plant growth/erosion simulator in this study. Although EPIC may be marginally less accurate than a simulator designed for a specific crop, its ability to model multiple crop species is critical to this analysis. A brief description of the EPIC model follows:

> EPIC simulates the physical process involved simultaneously and realistically using readily available inputs. Commonly used EPIC input data (weather, crop, tillage, and soil parameters) are available from a computer filing system assembled especially for applying EPIC throughout the U. S. Since erosion can be a relatively slow process, EPIC is capable of simulating hundreds of years if necessary. EPIC is generally applicable, computationally efficient (operates on a daily time step), and capable of computing the effects of management changes on outputs.
>
> The components of EPIC can be placed into eight major divisions for discussion-hydrology, weather, erosion, nutrients, plant growth, soil temperature, tillage, and economics...[The general plant growth model is used to simulate above-ground biomass, yield, and roots for corn, grain sorghum, wheat, barley, oats, peanuts, sunflowers, soybeans, alfalfa, cotton, and grasses (Williams, et al., p. 1).

Seventy-two runs of the EPIC model are performed, incorporating every combination of the primary model configurations with each of the 12 soil types. The production practices used are the same as those used to develop the production cost values in the linear programming models. A 50-year simulation is run and the average annual erosion is extracted for each of the 72 models. This results in 12 erosion levels for each primary model configuration. A weighted average of these 12 values is calculated, based upon the relative percentages of soil types as shown in Table 4.1. Since the model is based upon the erosion that reaches the water as sediment, not raw erosion, these six erosion levels are multiplied by the threshold sediment delivery ratio for the watershed. The threshold sediment delivery ratio is defined as that proportion of average annual total erosion which is delivered to a significant stream (Alexander and English). "A 'significant' stream begins where flow becomes adequate for a beneficial use such as a municipal water supply, water-based recreation, a fishery, or domestic use."[12]

Six sediment levels remain following these manipulations, one for each primary model configuration. However, these sediment levels are expressed in tons per acre while the optimal control model calls for sediment expressed as tons per unit output. To convert these results to the proper form, the average output, in bushels, is calculated for each crop. A weighted average, by relative soil type as shown in Table 4.1, is calculated from the crop yields used in the linear programming model. Dividing the sedimentation, in tons per acre, by the average yield, in bushels per acre, results in a sediment growth coefficient expressed in tons per bushel.

OPTIMAL DYNAMIC STRATEGIES

Numerical Solutions

The Data Modeling section of this chapter develops all of the coefficients necessary to obtain optimal numerical solutions to our dynamical system. Table 4.4 brings that information together and shows the coefficients for each of the six primary model configurations. Once the coefficients are developed, the numerical solutions become straightforward.

The Optimal Tax Function

Substituting the coefficients from Table 4.4 into equation 3.41 yields the following optimal tax functions in terms of *a*, *b*, and *c*:

(4.2) $$\tau^* = 2.604 - \frac{.404a}{c} + \frac{.911b}{c}$$ Conventional Corn;

[12]From an unpublished Soil Conservation Service memorandum from C. Don Clark, National Sedimentation Geologist, dated December 14, 1989.

Table 4.4. Model coefficient values.

Coefficient	Units	Corn		Soybeans		Wheat	
		Conventional	Conservation	Conventional	Conservation	Conventional	Conservation
Linear Cost (d)	\$/bu	1.14	1.24	2.62	2.85	2.84	3.21
Quadratic Cost (g)	\$/bu	4.7×10^{-9}	5.5×10^{-9}	3.1×10^{-8}	3.6×10^{-8}	8.8×10^{-9}	5.7×10^{-9}
Price (p)	\$/bu	2.75	2.75	7.65	7.65	3.40	3.40
Private Discount Rate (r)	\$/\$	.1	.1	.1	.1	.1	.1
Social Discount Rate (δ)	\$/\$	.05	.05	.05	.05	.05	.05
Unit Cost of Sediment (γ)	\$/tn†	6.38	6.38	6.38	6.38	6.38	6.38
Sediment Decay (h)	tn/tn	.01	.01	.01	.01	.01	.01
Sediment Growth (k)	tn/bu	.0583	.0488	.1926	.1522	.0519	.0376
Average Erosion (ζ)	tn/ac	20.06	16.09	21.20	16.68	7.33	5.34
Average Yield (β)	bu/ac	120.50	115.35	38.51	38.36	49.45	49.80

†English Tons

$$(4.3)\qquad \tau^*=2.917-\frac{.483a}{c}+\frac{.911b}{c}\qquad \text{Conservation Corn;}$$

$$(4.4)\qquad \tau^*=2.462-\frac{.340a}{c}+\frac{.911b}{c}\qquad \text{Conventional Soybeans;}$$

$$(4.5)\qquad \tau^*=2.974-\frac{.431a}{c}+\frac{.911b}{c}\qquad \text{Conservation Soybeans;}$$

$$(4.6)\qquad \tau^*=1.017-\frac{.562a}{c}+\frac{.911b}{c}\qquad \text{Conventional Wheat;}$$

$$(4.7)\qquad \tau^*=.467-\frac{.775a}{c}+\frac{.911b}{c}\qquad \text{Conservation Wheat.}$$

As previously discussed there is no *a priori* determination of unique values for a, b, and c. Rather, these variables represent the range of relative weights that society can place on the different benefits represented in the model. As indicated following equation 3.23, these values are restricted such that $a+b+c=1$; $0 \le a,b < 1$; $0 < c \le 1$. It is assumed for the empirical analysis that tax revenue (c) is not the primary purpose of such a policy and is not of primary concern to society relative to agricultural production and environmental quality. However, it is also clear from equations 4.2 through 4.7 that the value of c cannot be zero. Thus, the value of c is initially held to .1. Theoretically, of course, there is no reason not to explore the effects of varying the value of c but the number of permutations of all three coefficients quickly becomes intractable. As this study in intended to focus on the tradeoffs between agricultural production and environmental quality, only variations in the a and b coefficients are observed in this section. In developing the policy frontier, however, the value of c is varied and the results are graphically demonstrated.

Table 4.5 shows the value of τ^* for each primary model configuration. With c assumed to have a value of .1, the values of a and b can each vary between 0 and .9. Since both agricultural production and environmental quality, in some amount, are necessary for survival, the case in which either a or b

Table 4.5. Optimal tax values by primary model configuration and level of social importance.

a/b (c=.1)	Corn Conventional	Corn Conservation	Soybeans Conventional	Soybeans Conservation	Wheat Conventional	Wheat Conservation
			Dollars per Ton			
.1/.8	9.49	9.73	9.41	9.83	7.75	6.99
.2/.7	8.18	8.33	8.16	8.49	6.27	5.31
.3/.6	6.86	6.94	6.91	7.15	4.80	3.62
.4/.5	5.54	5.54	5.66	5.81	3.33	1.93
.5/.4	4.23	4.15	4.41	4.47	1.86	0.25
.6/.3	2.91	2.75	3.15	3.12	0.38	-1.44
.7/.2	1.60	1.36	1.90	1.78	-1.09	-3.13
.8/.1	0.28	-0.04	0.65	0.44	-2.56	-4.81

are zero is omitted and the coefficients are allowed to vary between .1 and .8. In fact, the actual value of such coefficients is not likely to approach either extreme due to the importance to society of both commodities. In several cases, the value of the optimal tax becomes negative as the weights move toward favoring agriculture, indicating that a subsidy to agriculture may be the optimal path for society.

These optimal tax values may be thought of as the value of externalities imposed upon society, weighted by the value society places on the competing goods of agricultural production and environmental quality. A non-weighted value, the level of pure economic transfer, may be obtained by solving the system again without the a, b, or c coefficients:

$$(4.8) \qquad \tau = \frac{(h+\delta)(p-d)(r+h)}{k(2h+\delta)} - \frac{ph(h+\delta)}{k(2h+\delta)} + \frac{\gamma h}{(2h+\delta)}.$$

The economic transfer equations result in the values shown in Table 4.6, which represent the actual transfer of value from society to agricultural producers for each of the primary model configurations. These economic transfer values are just over three dollars per ton for corn and soybeans, and are substantially lower for wheat.

Table 4.6. External costs of agricultural production borne by society.

Commodity	Value of Economic Transfer	Zero Production Tax Level	Full Production Tax Level
		Dollars/Ton	
Conventional Corn	3.11	3.04	2.04
Conservation Corn	3.35	3.40	2.07
Conventional Soybeans	3.03	2.87	2.24
Conservation Soybeans	3.45	3.47	2.54
Conventional Wheat	1.37	1.19	0.33
Conservation Wheat	0.61	0.56	-0.22

Some clues to the effect on the optimal tax of a change from conventional tillage to conservation tillage planting are provided in Table 4.5. When society values the environment significantly higher than agriculture, the change in the optimal tax for conservation tillage relative to conventional tillage is much smaller than when agriculture is weighted more favorably. In effect, the conservation tillage scenarios are always more sensitive to changes in *a* and *b* than the conventional scenarios. With the exception of wheat, however, the optimal tax values tend to converge with the values of *a* and *b*, giving similar results near the middle of the range. As shown in the Optimal Production Function section, the physical processes constrain the problem to these middle values such that the difference between tillage practices becomes insignificant to the problem as a whole, at least in this specific empirical application.

The Optimal Production Function

Substituting the coefficients from Table 4.4 and the optimal tax levels arising from equations 4.2 through 4.7 into equation 3.16 yields the optimal production functions facing the producers in this area:

(4.9) $$Y = 1.713 \times 10^{8} - 5.638 \times 10^{7}\tau$$ Conventional Corn;

$$(4.10) \quad Y = 1.373\times10^{8} - 4.033\times10^{7}\tau \qquad \text{Conservation Corn;}$$

$$(4.11) \quad Y = 8.113\times10^{7} - 2.824\times10^{7}\tau \qquad \text{Conventional Soybeans;}$$

$$(4.12) \quad Y = 6.667\times10^{7} - 1.922\times10^{7}\tau \qquad \text{Conservation Soybeans;}$$

$$(4.13) \quad Y = 3.182\times10^{7} - 2.681\times10^{7}\tau \qquad \text{Conventional Wheat;}$$

$$(4.14) \quad Y = 1.667\times10^{7} - 2.998\times10^{7}\tau \qquad \text{Conservation Wheat.}$$

Substituting the values of τ^* as shown in Table 4.5 into equations 4.9 through 4.14 yields the optimal production levels for each primary model configuration by tax level (Table 4.7). One obvious attribute of Table 4.7 is that, for all primary model configurations, the production level becomes negative as the social weights move toward environmental quality and away from agricultural production. For each crop, there exists a tax level at which producers would no longer find it profitable to produce the commodity in question. They would either shift production to a different crop or leave agriculture altogether. The negative values in Table 4.7 suggest that this level of taxation is well within the range of those taxes which would otherwise be considered socially optimal. Given the profit structure of

Table 4.7. Optimal production levels by primary model configuration and level of social importance.

a/b ($c = .1$)	Corn Conventional	Corn Conservation	Soybeans Conventional	Soybeans Conservation	Wheat Conventional	Wheat Conservation
			Bushels			
.1/.8	-3.64×10^{8}	-2.55×10^{8}	-1.85×10^{8}	-1.22×10^{8}	-1.76×10^{8}	-1.93×10^{8}
.2/.7	-2.90×10^{8}	-1.99×10^{8}	-1.49×10^{8}	-9.65×10^{7}	-1.36×10^{8}	-1.42×10^{8}
.3/.6	-2.16×10^{8}	-1.43×10^{8}	-1.14×10^{8}	-7.07×10^{7}	-9.69×10^{7}	-9.19×10^{7}
.4/.5	-1.41×10^{8}	-8.63×10^{7}	-7.87×10^{7}	-4.49×10^{7}	-5.74×10^{7}	-4.13×10^{7}
.5/.4	-6.71×10^{7}	-3.00×10^{7}	-4.33×10^{7}	-1.91×10^{7}	-1.79×10^{7}	9.27×10^{6}
.6/.3	7.08×10^{6}	2.62×10^{7}	-7.94×10^{6}	6.65×10^{6}	2.16×10^{7}	5.98×10^{7}
.7/.2	8.13×10^{7}	8.25×10^{7}	2.74×10^{7}	3.25×10^{7}	6.11×10^{7}	1.10×10^{8}
.8/.1	1.55×10^{8}	1.39×10^{8}	6.28×10^{7}	5.82×10^{7}	1.01×10^{8}	1.61×10^{8}

agriculture in the study area, producers of certain commodities simply cannot afford to absorb the total cost of their production externalities and remain in business.

To examine this issue, the production level, Y, is set to zero and equation 3.16 is rearranged to isolate τ:

$$(4.15) \qquad \tau = -(p+d)\frac{(r+h)}{k}.$$

This indicates the tax level at which production of the commodity would become unprofitable and, presumably, would cease. The zero production level tax is shown for each primary model configuration in Table 4.6.[13] Not surprisingly, those crops which are more profitable in the absence of a tax are able to sustain higher tax levels before becoming unprofitable. These levels may be thought of as a maximum tax imposed by the physioeconomic system regardless of the theoretical social weights applied. Similarly, there is a tax level for each commodity, less than the zero tax level, at which all of the resources of the area will be placed in use. Equation 3.16 is again rearranged, this time leaving the variable Y explicit in the equation:

$$(4.16) \qquad \tau = -(-p+d+2gY)\frac{(r+h)}{k}.$$

The full production tax levels for each primary model configuration are shown in Table 4.6. Any tax below these levels will not affect the production decisions of farmers. Each zero tax level and full production tax level is associated with a pair of values of a and b. This effectively sets a bound on the range of social weights which can affect production of agricultural products. The range of possible social weights falls between .4/.5 and .7/.2 for a/b. This suggests that severely skewed social weights are not sustainable under the conditions in the study area. It may, perhaps, be inferred from this limited application that the importance of both goods to a healthy society may preclude an extreme bias in

[13]As crop prices are exogenous to the model, these results assume no change in price as a result of the hypothetical zero production.

either direction. Since price is a determinant of this range, the market itself may act exogenously as a stabilizing force.

Sensitivity Analysis

As discussed early in this chapter, a mathematical model is not amenable to statistical verification. In attempting to verify a mathematical model through other means, an important factor in understanding the model is the sensitivity of the model results to changes in its components. The conventional corn model configuration is used as a base for the sensitivity analysis. Each coefficient contained in equations 3.41 and 3.16 is increased by 50% and the resulting percentage change is recorded in each of three result parameters: external production costs, zero tax level, and full production tax level. The results are shown in Table 4.8.

Table 4.8. Effect on various tax levels of a 50 percent increase in equation parameters.

Tax Parameter	Original Value	*d*	*g*	*p*	*r*	*δ*	*γ*	*h*	*k*
					Dollars (Percent Change)				
Economic Transfer	3.11	2.19 (-.30)	3.11 (.00)	5.14 (.65)	4.29 (.38)	2.97 (-.05)	3.57 (.15)	3.20 (.03)	2.39 (-.23)
Zero Production	3.04	1.96 (-.36)	3.04 (.00)	5.64 (.86)	4.42 (.45)	3.04 (.00)	3.04 (.00)	3.18 (.05)	1.37 (-.55)
Full Production	2.04	0.96 (-.53)	1.53 (-.25)	4.64 (1.27)	2.97 (.46)	2.04 (.00)	2.04 (.00)	2.13 (.04)	1.38 (-.32)

The linear and quadratic cost coefficients, *d* and *g* respectively, are estimated using the linear programming algorithm as explained in the Data Modeling section of this chapter. The tax levels are moderately sensitive to changes in the linear cost coefficient, *d*. The full production tax level is also somewhat sensitive to the quadratic cost coefficient, *g*; however, both the level of external costs and the zero tax level are not functions of *g* and are not affected. Another interesting note is that the range of optimal values of *Y* is tied to the value of *g*. In this application, *g* is very small as the cropland used in the linear programming model is relatively homogeneous. Mathematically, as g increases, the range of optimal production values decreases.

The tax levels are moderately sensitive to changes in the private instantaneous annual rate of discount, r. This is not unexpected as the results are strongly tied to the profitability of agricultural production over time. In contrast, the social instantaneous annual rate of discount, δ, has very little effect on the results of the model. Its effect on external costs is only five percent, and it has no effect on the zero or full production tax rates. The model is similarly insensitive to changes in the unit cost of sediment, γ. The change in gamma increases external costs by only 15 percent, and has no effect on the zero and full production tax levels.

The model is quite sensitive to changes in price, p. The 50 percent increase in price results in a 65 percent, 86 percent, and 127 percent change in external costs, zero production tax level, and full production tax level, respectively. Due to the importance of prices to the model results, the sensitivity analysis is extended for this variable to consider the sensitivity of the other model configurations to more drastic changes in price. For the corn and wheat configurations, the model is solved for the economic transfer value under current loan rate levels and under current target price levels. There is no target price for soybeans, so the model results under the loan rate price level is compared to the market price used in the base analysis. The loan rates used for corn, soybeans, and wheat are $1.96 per bushel, $4.50 per bushel, and $2.44 per bushel, respectively (Loewen, et al.). The target prices used for corn and wheat are $2.75[14] per bushel and $4.00 per bushel respectively (Loewen, et al.).

For conventional corn, the economic transfer value varies from $1.95 per ton under the loan rate to $3.11 per ton under the target price. The ranges are $1.96 to $3.35 per ton for conservation corn, $-0.22 to $2.36 per ton for conventional wheat, and $-1.58 to $1.98 per ton for conservation wheat. The economic transfer values vary from $1.63 per ton under the loan rate price to $3.03 per ton under the base market price for conventional soybeans, and $1.68 to $3.45 per ton for conservation soybeans.

[14]It may be noted that $2.75 per bushel is also the price used for corn in the base analysis. That value does not represent the target price, but the market price for that year.

The wide variation in model results under different price scenarios emphasizes the importance of price estimation in this model. While historical price figures are generally accurate and relatively easy to obtain, it is important to remember that price is exogenous to this model and that this model is sensitive to the price variable. Changes in price over time would require revisiting the model to update the results.

Only two physical coefficients appear in the final equations. The external costs, zero production tax level, and full production tax level are moderately sensitive to the sediment growth coefficient, *k*. The entire model is insensitive to changes in the sediment decay coefficient, *h*. The effect of *h* on external costs, zero production tax levels, and full production tax levels is only three percent, five percent, and four percent, respectively.

The Dynamic Policy Frontier

One of the key features of this model is in the ability of the modeler to develop solutions independent of policy goals. This approach "does not require the prior articulation of policy preferences, and by parameterizing on policy goals it allows policy frontiers to be generated which provide a configuration of tradeoffs and policy options suitable for use by decision makers and other policy actors" (Sylvia and Anderson, p.2). The parameterization of relative weights, *a*, *b*, and *c*, in the model provides for a range of answers as shown in the Numerical Solutions section of this chapter. An additional benefit is the ability to graphically represent the relationship between the optimal tax function and the values of *a*, *b*, and *c*.

The weight society places on agricultural production is represented by variable *a*; variable *b* is the weight society places on water quality, and variable *c* is the value society places in receiving tax revenues from agricultural production. The variables are constrained such that $a+b+c=1$, and $0 \le a,b < 1;\ 0 < c \le 1$. In the graphs which follow, the optimal tax rate is shown on the vertical axis and the variable *a* is shown on the horizontal axis. Each line in the graphs represents a constant value of *c*. The value of *b* can be calculated for any given point as $b=1-a-c$; however, the scale of *b* changes for each value of *c* so it is not shown explicitly.[15] The graphical policy frontiers for each primary model configuration are shown in Figures 4.3 through 4.8.

The dynamic policy frontiers for corn and soybeans, regardless of tillage practice, are quite similar. The frontiers for wheat are similar to each other, but vary from those of corn and soybeans in that they show significant negative values for higher levels of *c*. In each case, while discrete lines are plotted, the frontier should be thought of as a surface. It is important to acknowledge that the shape of these frontier surfaces are not completely defined by the analytical model. The characteristic shared by each of these frontier surfaces, in that optimal tax values grow smaller with increases in *c*, may not be consistent in other applications of the model.

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[15]The choice of *a* is arbitrary. Variable *b* could have been explicitly shown on the horizontal axis, with *a* implicit, if a researcher so chose.

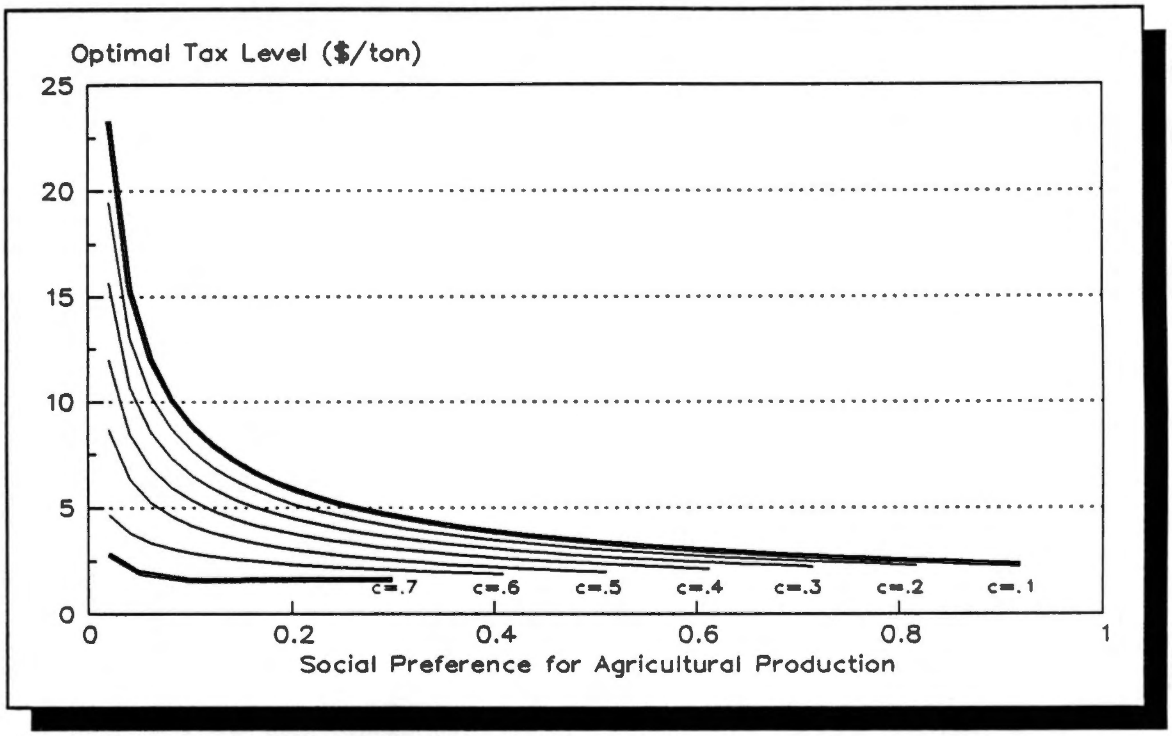

Figure 4.3. Dynamic policy frontier for conventional corn.

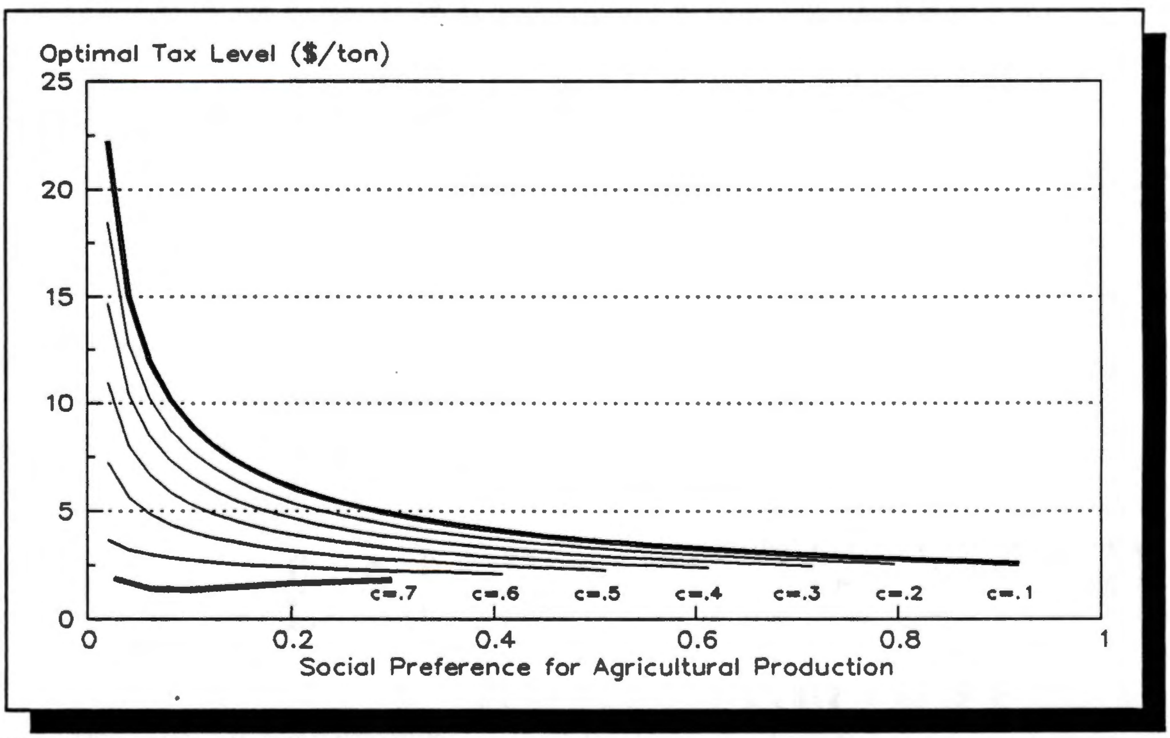

Figure 4.4. Dynamic policy frontier for conservation corn.

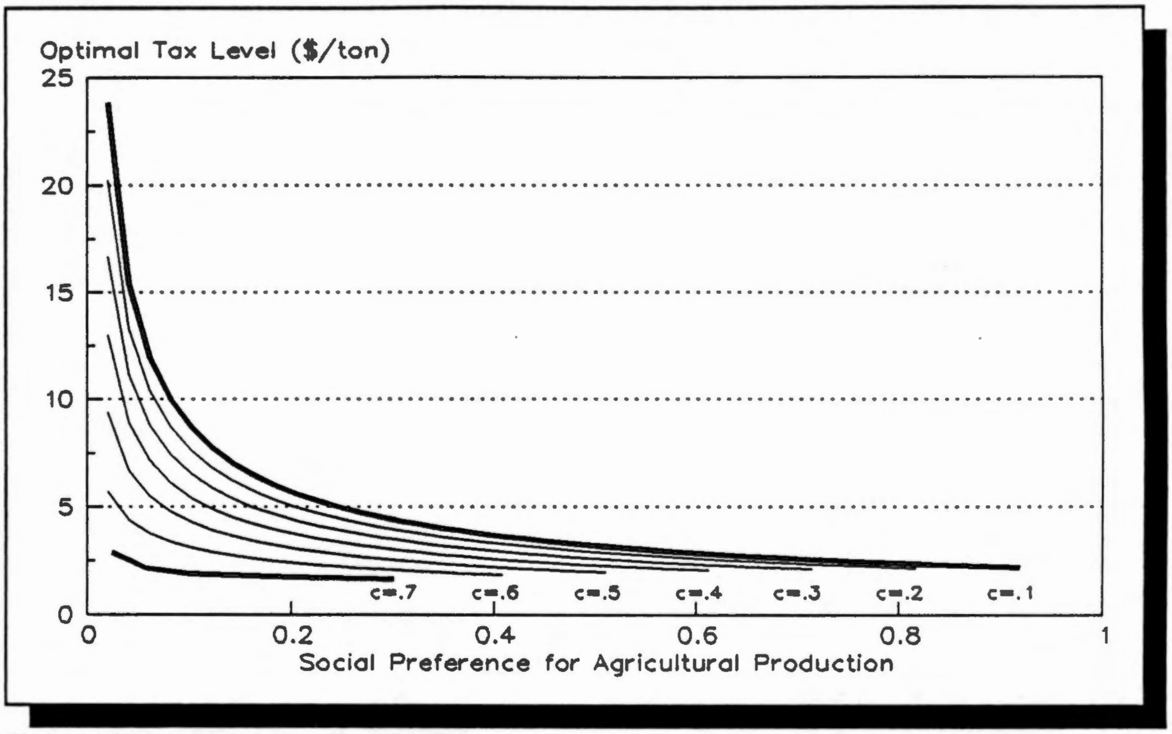

Figure 4.5. Dynamic policy frontier for conventional soybeans.

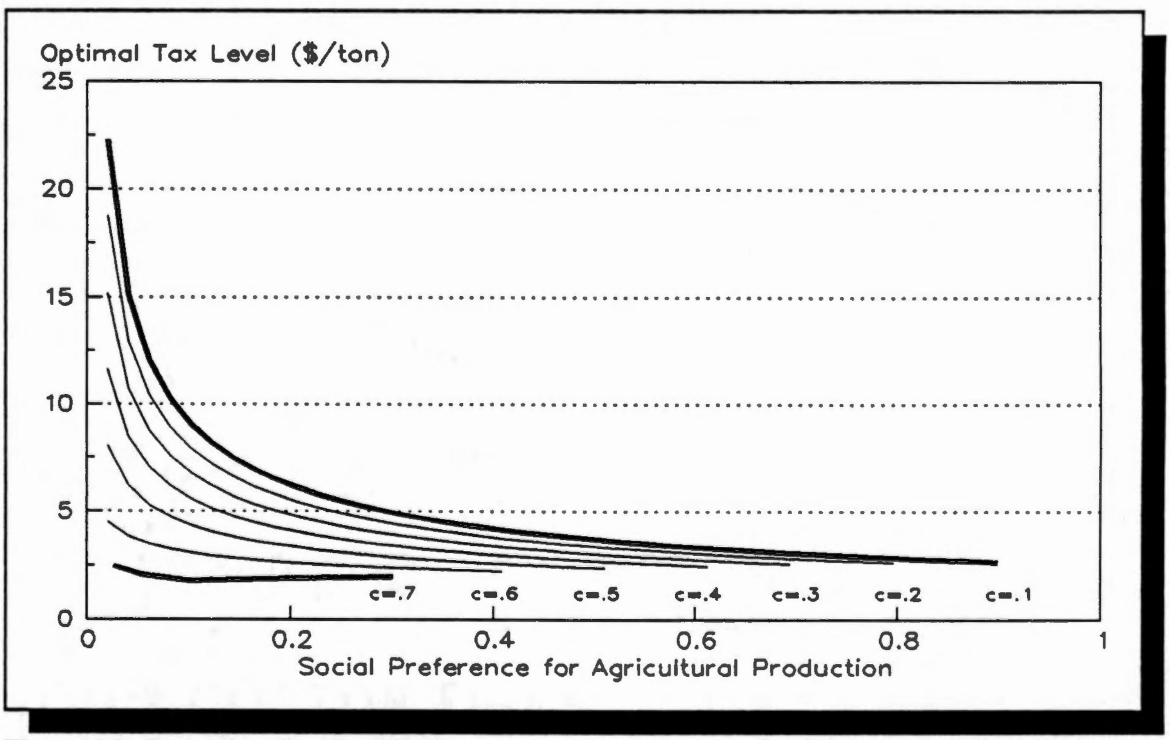

Figure 4.6. Dynamic policy frontier for conservation soybeans.

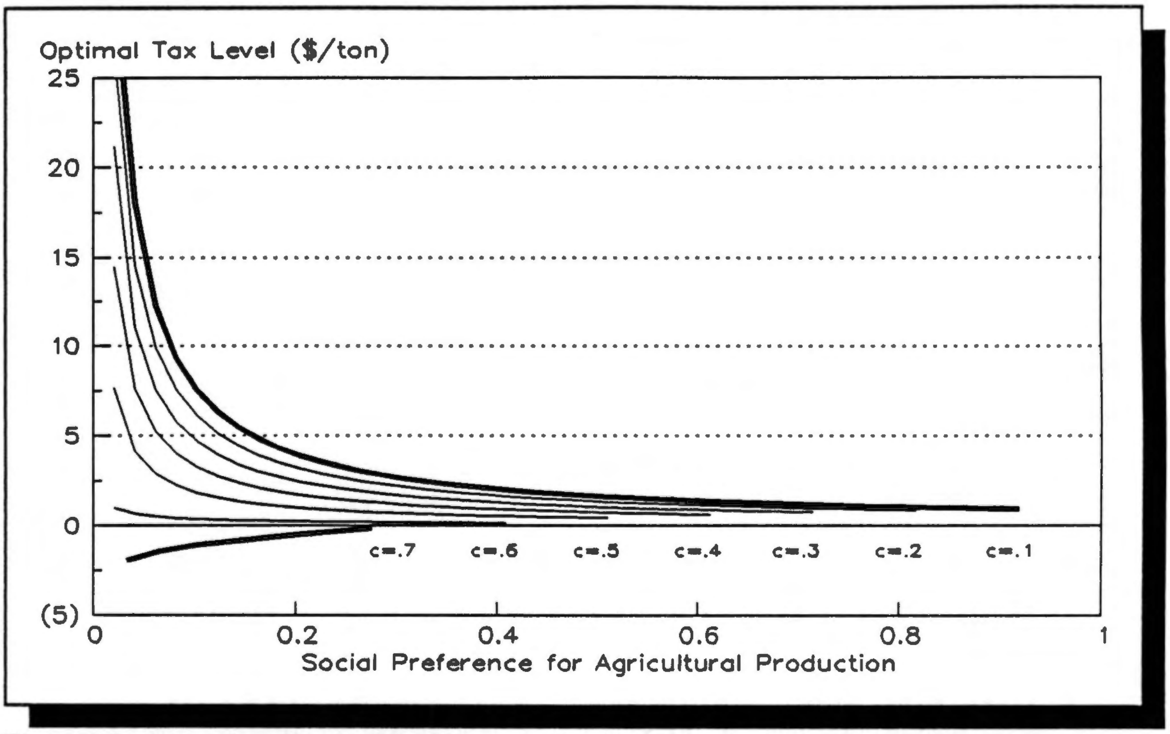

Figure 4.7. Dynamic policy frontier for conventional wheat.

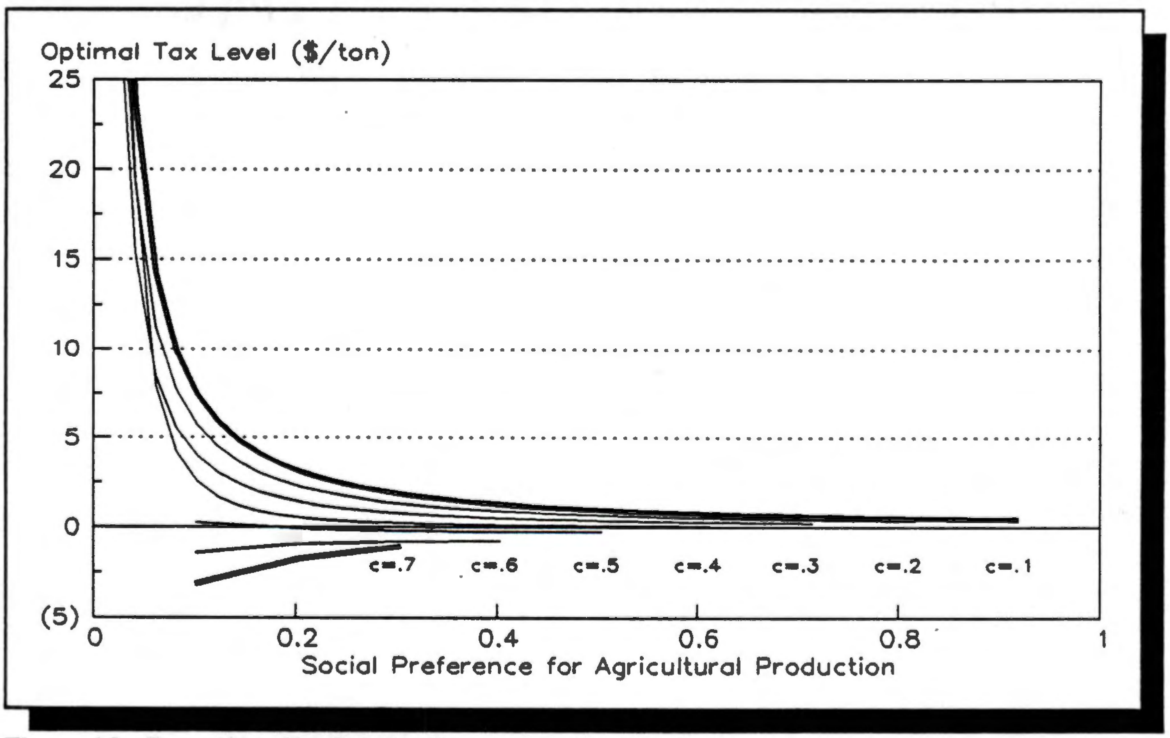

Figure 4.8. Dynamic policy frontier for conservation wheat.

CHAPTER V

SUMMARY AND CONCLUSION

BACKGROUND

Agricultural topsoil is one of the critical natural resources of a civilization. This delicate layer of our planet is the primary source of sustenance for human and animal populations. Arable soil is necessary to feed, clothe, and shelter human beings and is a prerequisite for achieving the aspirations of a society. Without adequate arable land, a civilization will find it difficult to thrive, or even survive (Browning; Napier and Forster). Thus, the potential of a society is largely dependent upon the topsoil of its agricultural lands (Napier and Forster).

While the importance of topsoil and the problem of topsoil loss have long been recognized, more than 40 years of cooperative efforts between farmers and the federal government have done little to check the erosion of our farmland (McConnell; Napier and Forster; Rasmussen, 1982; Walker). One-third of U.S. cropland topsoil has been lost in the last 200 years (Walker), and erosion continues at a significant rate (USDA/SCS, 1980).

Increased public awareness of these issues continues to put pressure on policymakers to solve our environmental problems while maintaining an abundant, inexpensive food supply. Policy debates, past and present, have focused primarily on physical actions to be taken rather than upon policy goals and objectives (Robinson, K.). Yet the use of physical goals of soil loss is often challenged by economists who argue that it is not the physical loss from the farm that is important, but the costs incurred by loss of topsoil and offsite damages from agriculturally-generated sedimentation (Robinson, K.). Offsite sediment damages are far greater than onsite productivity damages.

The objective of this study was to develop a soil conservation policy model, incorporating the objectives of both producers and policymakers, that: 1) estimates the economic transfers between agricultural producers and society resulting from agricultural production and its associated sediment-based externalities, and 2) estimates a socially optimal level of taxation, given varying levels of perceived importance to society of agriculture versus environmental quality.

Several specific elements are necessary for the development of a soil erosion policy model. Those elements include modeling (1) the interaction of producer and policymaker (Anderson and Lee; Candler, et al.; Candler and Norton; Sharp and Bromley; Sylvia and Anderson), (2) the dynamic nature of the sedimentation process (Ervin, et al.; Rausser, 1980; Swanson, 1982), and (3) the recognition of multiple, competing goals of the policymaker (Rausser and Yassour; Sylvia and Anderson; Van Kooten, et al.). The model used is an adaptation of the multi-level programming concept developed by Candler and Norton and extended by Sylvia and Anderson. A multi-level optimal control model was developed which optimizes the producer's dynamic problem in the first stage, then uses the producer's optimal decision paths in the second stage as components of the policymakers' dynamic problem. The second stage problem utilizes weights indicating the relative importance of the policymaker's competing goals. Those weights are used to construct a dynamic policy frontier demonstrating the relationships between various policy goals and the resulting optimal solution paths.

The model was applied to a three-county area in west Tennessee composed of Obion, Weakley, and Gibson counties. These three counties are located in the area categorized by the Soil Conservation Service as the Southern Mississippi Valley Silty Uplands, or Major Land Resource Area (134) (USDA/SCS, 1981). The region is also referred to as the Southern Plateau Slope (Mundy and Gray). With elevations ranging from 25 to 100 meters (USDA/SCS, 1981), this is the region that joins the Mississippi bottomlands with the Cumberland Plateau. The majority of the land in the area is used for agriculture, with corn, soybeans and wheat being the primary crops.

RESULTS

The model provided information on the rates of taxation that would optimize the resources of both society and farmers given the preference of society for agricultural output versus environmental quality. These optimal tax rates represent the transfer of costs from the agricultural producer to society as a whole. The optimal tax rates were then substituted into the optimal production function for agricultural producers to determine the level of production that may be expected to result given the underlying profit structure of agricultural production and the tax rate applied. The model was applied separately to corn, soybeans and wheat in the study area.

Effective optimal taxes were determined which would result in a range of production from zero to full production, and were identified as a bound on tax rates which would be expected to affect levels of agricultural production. The range of taxes, from full to zero production, respectively, were $2.04 - $3.04 for conventional corn, $2.07 - $3.40 for conservation corn, $2.24 - $2.87 for conventional soybeans, $2.54 - $3.47 for conservation soybeans, $0.33 - $1.19 for conventional wheat, and $-0.22 - $0.56 for conservation wheat. All values are in dollars per ton of sediment.

Tax rates less than the full production tax rate are expected to reduce society's cost of agricultural production without reducing output of the commodity being modeled. Tax levels in the effective range are expected to both reduce agricultural output of the commodity, to reduce offsite sediment damages from agricultural production, and to reduce the cost to society of remaining agricultural production.[16] Tax levels greater than the zero production level are expected to result in a complete shift in production from the commodity being modeled to some other enterprise. The model does not address what new enterprise that would be, nor its relative environmental impacts.

External costs of production were also calculated to indicate the absolute transfer to society, without regard to social preferences, of offsite sedimentation costs arising from agricultural production. The external costs, in dollars per ton of sediment, are $3.11 for conventional corn, $3.35 for conservation corn, $3.03 for conventional soybeans, $3.45 for conservation soybeans, $1.37 for conventional wheat, and $0.61 for conservation wheat.

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[16]As crop prices are exogenous to the model, these results assume no change in price as a result of the hypothetical zero production.

An analysis was performed of the sensitivity of the external costs, the zero production tax level and the full production tax level to changes in the model coefficients. The model was extremely sensitive to changes in price; moderately sensitive to changes in the linear cost coefficient, the private instantaneous rate of discount, and the sediment growth coefficient; and relatively insensitive to changes in the quadratic cost coefficient, the social instantaneous rate of discount, the unit cost of offsite sediment damages, and the sediment decay coefficient.

A dynamic policy frontier was constructed for each commodity. The frontier is a schedule of the relationship between the optimal tax levels and their associated social preference values. The dynamic policy frontiers for the study area showed more variation by crop than by tillage practice, indicating that tillage practice may affect erosion costs less than crop selection and land characteristics.

LIMITATIONS

The study attempted to estimate the economic transfers between agricultural producers and society resulting from agricultural production and its associated sediment-based externalities. As is characteristic of mathematical models, some concessions had to be made in the name of mathematical tractability. While the model is able to address both the producer's problem and the policymaker's problem, each optimal control sub-model is constrained to one state variable and one control variable. While the policymaker's model expresses a second equation of motion in equation 3.22, that equation satisfies the constraint, becoming zero due to assumptions in the producer's model. The model would be rendered analytically insolvable if this constraint were violated; however, such a constraint could be abandoned in a purely numerical model.

The results of these constraints affect the model assumptions in several ways. The assumption that the producer can only control erosion through entering or removing land from production is a result of requiring only a single control variable for the producer. Thus, the model is unable to deal endogenously with changes in production practices, such as the shift from conventional to conservation tillage. While the empirical results in this study demonstrate that such changes are less effective than changes in the amount of land cultivated, this restriction must be considered to be a significant limitation of the system.

Another assumption resulting from these constraints is that of the exogenous price level. It was shown in the sensitivity analysis that the model is particularly sensitive to price, yet the model is unable to adapt to such changes endogenously. This introduces an implicit assumption that the 1988 prices will remain in effect throughout the application of the model, and that producers hold the expectation that prices will remain constant. The constant price assumption causes the result shown in equation 3.15, that the change in the producer's optimal production over time is equal to zero. Without this assumption, the second equation of motion in equation 3.22 would be non-zero and the model would be analytically insolvable.

Other constraints arise from the difficulty in estimating empirical parameters in the application of the model. The economic cost relationships were artificially generated, based upon theoretical rather than empirical relationships. This lack of empirical data limits the applicability of the model to other areas. Similarly, data on the decay of sediment was unavailable and had to be estimated as a generalized approximation of a large region. While better data were available from which to construct the sediment growth coefficient the model is limited in the inability to use the full range of data. The study area includes production on 12 soil types, yet the sediment growth coefficient is reduced to a single value. Since this value is based upon a weighted average of available cropland soil type, the sediment growth coefficient implicitly assumes proportional production on all soils types at every level of production.

FURTHER RESEARCH

A study of this nature requires combining information from various fields of study, including economics, plant and soil science, hydrology, mathematics, and public policy. Many of the limitations of the model were based upon limitations in the mathematical tools applicable to applied economics. Further research into multiple-state, multiple control extensions of optimal control theory is suggested.

Numerical applications are most promising in this area, but data is lacking. Thus, additional research is needed in developing an empirical data base of production costs, yields, erosion, and hydrological characteristics of a variety of watersheds across the country.

Specific research suggestions include the addition of multiple controls to both the producer and policymaker sub-models, the inclusion of price an endogenous variable in the modeling system, and the econometric estimation of agricultural cost functions. Applications and adaptations of this model may also be useful in examining a variety of policy-related issues in natural resource and environmental economics.

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APPENDIX
LINEAR PROGRAMMING MODELS

```
$TITLE MLRA 134 CORN MODEL - CONSERVATION TILLAGE
$OFFUPPER

SETS
      ACTIVITIES Each crop as produced on a specific soil type
         / CORNAD, CORNBI, CORNCA, CORNCL, CORNCV, CORNFA, CORNGR,
           CORNLX, CORNLO, CORNME, CORNPR, CORNWA /
      RESOURCES
         / ADLER, BIRDS, CALLOWAY, COLLINS, CONVENT, FALAYA, GRENADA,
           LEXINGTON, LORRING, MEMPHIS, PROV, WAVERLY /

TABLE LANDUSE(ACTIVITIES, RESOURCES)  Land use by crop and soil type

         ADLER BIRDS CALLOWAY COLLINS CONVENT FALAYA GRENADA LEXINGTON LORRING MEMPHIS PROV WAVERLY
CORNAD     1     0      0       0       0      0       0        0        0       0     0      0
CORNBI     0     1      0       0       0      0       0        0        0       0     0      0
CORNCA     0     0      1       0       0      0       0        0        0       0     0      0
CORNCL     0     0      0       1       0      0       0        0        0       0     0      0
CORNCV     0     0      0       0       1      0       0        0        0       0     0      0
CORNFA     0     0      0       0       0      1       0        0        0       0     0      0
CORNGR     0     0      0       0       0      0       1        0        0       0     0      0
CORNLX     0     0      0       0       0      0       0        1        0       0     0      0
CORNLO     0     0      0       0       0      0       0        0        1       0     0      0
CORNME     0     0      0       0       0      0       0        0        0       1     0      0
CORNPR     0     0      0       0       0      0       0        0        0       0     1      0
CORNWA     0     0      0       0       0      0       0        0        0       0     0      1;

PARAMETERS

 RECEIPTS(ACTIVITIES)  Total Receipts (Dollars Per Acre)
  / CORNAD = 385.00, CORNBI = 217.25, CORNCA = 321.75, CORNCL = 368.50,
    CORNCV = 305.25, CORNFA = 288.75, CORNGR = 319.00, CORNLX = 346.50,
    CORNLO = 346.50, CORNME = 360.25, CORNPR = 264.00, CORNWA = 187.00 /

 RHS(RESOURCES)
  / ADLER = 8881, BIRDS = 5609, CALLOWAY = 38327, COLLINS = 59360,
    CONVENT = 3739, FALAYA = 78991, GRENADA = 73382, LEXINGTON = 7011,
    LORRING = 108903, MEMPHIS = 28511, PROV = 18229, WAVERLY = 36457 /

 COSTS(ACTIVITIES)  Costs (Dollars Per Acre)
  / CORNAD = 168.09, CORNBI = 178.52, CORNCA = 180.45, CORNCL = 180.80,
    CORNCV = 187.56, CORNFA = 188.05, CORNGR = 181.43, CORNLX = 168.25,
    CORNLO = 179.90, CORNME = 188.93, CORNPR = 163.93, CORNWA = 186.98 /

 SCALAR   REVENUE    / 5000000 /

 VARIABLES

     MIX(ACTIVITIES)            Mix of production activities
     TCOST                      Value of objective function
     POSITIVE VARIABLE MIX

 EQUATIONS

     TOTALR                     Revenue Calculation & Constraint
     CAP(RESOURCES)             Capacity Constraints
     TOTALC                     Accounting:  Costs;

 TOTALR..          SUM(ACTIVITIES, RECEIPTS(ACTIVITIES) * MIX(ACTIVITIES)) =G= REVENUE;
 CAP(RESOURCES)..  SUM(ACTIVITIES, LANDUSE(ACTIVITIES, RESOURCES) * MIX(ACTIVITIES)) =L=
                   + RHS(RESOURCES);

 TOTALC..          TCOST =E= SUM(ACTIVITIES, COSTS(ACTIVITIES) * MIX(ACTIVITIES));
 MODEL CRNCNS No Till Cost Problem / ALL /; SOLVE CRNCNS MINIMIZING TCOST USING LP;
```

Figure A.1. Linear programming model for conservation corn.

```
$TITLE MLRA 134 CORN MODEL - CONVENTIONAL TILLAGE
$OFFUPPER

SETS
      ACTIVITIES Each crop as produced on a specific soil type
         / CORNAD, CORNBI, CORNCA, CORNCL, CORNCV, CORNFA, CORNGR,
           CORNLX, CORNLO, CORNME, CORNPR, CORNWA /
      RESOURCES
         / ADLER, BIRDS, CALLOWAY, COLLINS, CONVENT, FALAYA, GRENADA,
           LEXINGTON, LORRING, MEMPHIS, PROV, WAVERLY /

TABLE LANDUSE(ACTIVITIES, RESOURCES)  Land use by crop and soil type

        ADLER BIRDS CALLOWAY COLLINS CONVENT FALAYA GRENADA LEXINGTON LORRING MEMPHIS PROV WAVERLY
CORNAD    1     0      0        0       0       0      0        0         0       0      0     0
CORNBI    0     1      0        0       0       0      0        0         0       0      0     0
CORNCA    0     0      1        0       0       0      0        0         0       0      0     0
CORNCL    0     0      0        1       0       0      0        0         0       0      0     0
CORNCV    0     0      0        0       1       0      0        0         0       0      0     0
CORNFA    0     0      0        0       0       1      0        0         0       0      0     0
CORNGR    0     0      0        0       0       0      1        0         0       0      0     0
CORNLX    0     0      0        0       0       0      0        1         0       0      0     0
CORNLO    0     0      0        0       0       0      0        0         1       0      0     0
CORNME    0     0      0        0       0       0      0        0         0       1      0     0
CORNPR    0     0      0        0       0       0      0        0         0       0      1     0
CORNWA    0     0      0        0       0       0      0        0         0       0      0     1;

PARAMETERS

 RECEIPTS(ACTIVITIES)  Total Receipts (Dollars Per Acre)
  / CORNAD = 423.50, CORNBI = 220.00, CORNCA = 321.75, CORNCL = 407.00,
    CORNCV = 338.25, CORNFA = 338.25, CORNGR = 305.25, CORNLX = 338.25,
    CORNLO = 354.75, CORNME = 371.25, CORNPR = 253.00, CORNWA = 187.00 /

 RHS(RESOURCES)
  / ADLER = 8881, BIRDS = 5609, CALLOWAY = 38327, COLLINS = 59360,
    CONVENT = 3739, FALAYA = 78991, GRENADA = 73382, LEXINGTON = 7011,
    LORRING = 108903, MEMPHIS = 28511, PROV = 18229, WAVERLY = 36457 /

 COSTS(ACTIVITIES)  Costs (Dollars Per Acre)
  / CORNAD = 161.27, CORNBI = 180.70, CORNCA = 173.63, CORNCL = 173.98,
    CORNCV = 180.74, CORNFA = 181.23, CORNGR = 174.61, CORNLX = 161.43,
    CORNLO = 173.08, CORNME = 182.11, CORNPR = 157.11, CORNWA = 180.16 /

 SCALAR   REVENUE   / 5000000 /

 VARIABLES

     MIX(ACTIVITIES)            Mix of production activities
     TCOST                      Value of objective function
     POSITIVE VARIABLE MIX

 EQUATIONS

     TOTALR                     Revenue Calculation & Constraint
     CAP(RESOURCES)             Capacity Constraints
     TOTALC                     Accounting:  Costs;

 TOTALR..          SUM(ACTIVITIES, RECEIPTS(ACTIVITIES) * MIX(ACTIVITIES)) =G= REVENUE;
 CAP(RESOURCES).. SUM(ACTIVITIES, LANDUSE(ACTIVITIES, RESOURCES) * MIX(ACTIVITIES)) =L=
                  + RHS(RESOURCES);

 TOTALC..          TCOST =E= SUM(ACTIVITIES, COSTS(ACTIVITIES) * MIX(ACTIVITIES));
 MODEL CRNCNV Conventional Till Cost Problem / ALL /; SOLVE CRNCNV MINIMIZING TCOST USING LP;
```

Figure A.2. Linear programming model for conventional tillage corn.

```
$TITLE MLRA 134 SOYBEAN MODEL - CONSERVATION TILLAGE
$OFFUPPER

SETS
      ACTIVITIES Each crop as produced on a specific soil type
         / SOYAD, SOYBI, SOYCA, SOYCL, SOYCV, SOYFA, SOYGR,
           SOYLX, SOYLO, SOYME, SOYPR, SOYWA /
      RESOURCES
         / ADLER, BIRDS, CALLOWAY, COLLINS, CONVENT, FALAYA, GRENADA,
           LEXINGTON, LORRING, MEMPHIS, PROV, WAVERLY /

TABLE LANDUSE(ACTIVITIES, RESOURCES)  Land use by crop and soil type

       ADLER BIRDS CALLOWAY COLLINS CONVENT FALAYA GRENADA LEXINGTON LORRING MEMPHIS PROV WAVERLY
SOYAD    1     0      0        0       0       0      0        0        0       0      0     0
SOYBI    0     1      0        0       0       0      0        0        0       0      0     0
SOYCA    0     0      1        0       0       0      0        0        0       0      0     0
SOYCL    0     0      0        1       0       0      0        0        0       0      0     0
SOYCV    0     0      0        0       1       0      0        0        0       0      0     0
SOYFA    0     0      0        0       0       1      0        0        0       0      0     0
SOYGR    0     0      0        0       0       0      1        0        0       0      0     0
SOYLX    0     0      0        0       0       0      0        1        0       0      0     0
SOYLO    0     0      0        0       0       0      0        0        1       0      0     0
SOYME    0     0      0        0       0       0      0        0        0       1      0     0
SOYPR    0     0      0        0       0       0      0        0        0       0      1     0
SOYWA    0     0      0        0       0       0      0        0        0       0      0     1;

PARAMETERS

 RECEIPTS(ACTIVITIES)  Total Receipts (Dollars Per Acre)
  / SOYAD = 260.10, SOYBI = 275.40, SOYCA = 321.30, SOYCL = 351.90,
    SOYCV = 290.70, SOYFA = 290.70, SOYGR = 260.10, SOYLX = 260.10,
    SOYLO = 313.65, SOYME = 306.00, SOYPR = 183.60, SOYWA = 244.80 /

 RHS(RESOURCES)
  / ADLER = 8881, BIRDS = 5609, CALLOWAY = 38327, COLLINS = 59360,
    CONVENT = 3739, FALAYA = 78991, GRENADA = 73382, LEXINGTON = 7011,
    LORRING = 108903, MEMPHIS = 28511, PROV = 18229, WAVERLY = 36457 /

 COSTS(ACTIVITIES)  Costs (Dollars Per Acre)
  / SOYAD = 126.65, SOYBI = 136.09, SOYCA = 132.53, SOYCL = 136.95,
    SOYCV = 136.23, SOYFA = 136.65, SOYGR = 134.63, SOYLX = 126.65,
    SOYLO = 134.86, SOYME = 135.17, SOYPR = 126.65, SOYWA = 136.41 /

 SCALAR   REVENUE    / 5000000 /

 VARIABLES

     MIX(ACTIVITIES)            Mix of production activities
     TCOST                      Value of objective function
     POSITIVE VARIABLE MIX

 EQUATIONS

     TOTALR                     Revenue Calculation & Constraint
     CAP(RESOURCES)             Capacity Constraints
     TOTALC                     Accounting:  Costs;

 TOTALR..          SUM(ACTIVITIES, RECEIPTS(ACTIVITIES) * MIX(ACTIVITIES)) =G= REVENUE;
 CAP(RESOURCES)..  SUM(ACTIVITIES, LANDUSE(ACTIVITIES, RESOURCES) * MIX(ACTIVITIES)) =L=
                   + RHS(RESOURCES);

 TOTALC..          TCOST =E= SUM(ACTIVITIES, COSTS(ACTIVITIES) * MIX(ACTIVITIES));
 MODEL SOYCNS No Till Cost Problem / ALL /; SOLVE SOYCNS MINIMIZING TCOST USING LP;
```

Figure A.3. Linear programming model for conservation soybeans.

```
$TITLE MLRA 134 SOYBEAN MODEL - CONVENTIONAL TILLAGE
$OFFUPPER

SETS
     ACTIVITIES Each crop as produced on a specific soil type
        / SOYAD, SOYBI, SOYCA, SOYCL, SOYCV, SOYFA, SOYGR,
          SOYLX, SOYLO, SOYME, SOYPR, SOYWA /
     RESOURCES
        / ADLER, BIRDS, CALLOWAY, COLLINS, CONVENT, FALAYA, GRENADA,
          LEXINGTON, LORRING, MEMPHIS, PROV, WAVERLY /

TABLE LANDUSE(ACTIVITIES, RESOURCES)  Land use by crop and soil type

       ADLER BIRDS CALLOWAY COLLINS CONVENT FALAYA GRENADA LEXINGTON LORRING MEMPHIS PROV WAVERLY
SOYAD    1     0      0        0       0       0      0        0         0       0      0     0
SOYBI    0     1      0        0       0       0      0        0         0       0      0     0
SOYCA    0     0      1        0       0       0      0        0         0       0      0     0
SOYCL    0     0      0        1       0       0      0        0         0       0      0     0
SOYCV    0     0      0        0       1       0      0        0         0       0      0     0
SOYFA    0     0      0        0       0       1      0        0         0       0      0     0
SOYGR    0     0      0        0       0       0      1        0         0       0      0     0
SOYLX    0     0      0        0       0       0      0        1         0       0      0     0
SOYLO    0     0      0        0       0       0      0        0         1       0      0     0
SOYME    0     0      0        0       0       0      0        0         0       1      0     0
SOYPR    0     0      0        0       0       0      0        0         0       0      1     0
SOYWA    0     0      0        0       0       0      0        0         0       0      0     1;

PARAMETERS

 RECEIPTS(ACTIVITIES)  Total Receipts (Dollars Per Acre)
  / SOYAD = 351.90, SOYBI = 275.40, SOYCA = 321.30, SOYCL = 351.90,
    SOYCV = 290.70, SOYFA = 290.70, SOYGR = 267.75, SOYLX = 260.10,
    SOYLO = 306.00, SOYME = 306.00, SOYPR = 183.60, SOYWA = 244.80 /

 RHS(RESOURCES)
  / ADLER = 8881, BIRDS = 5609, CALLOWAY = 38327, COLLINS = 59360,
    CONVENT = 3739, FALAYA = 78991, GRENADA = 73382, LEXINGTON = 7011,
    LORRING = 108903, MEMPHIS = 28511, PROV = 18229, WAVERLY = 36457 /

 COSTS(ACTIVITIES)  Costs (Dollars Per Acre)
  / SOYAD = 115.34, SOYBI = 124.78, SOYCA = 121.22, SOYCL = 125.64,
    SOYCV = 124.92, SOYFA = 125.34, SOYGR = 123.32, SOYLX = 115.34,
    SOYLO = 123.55, SOYME = 123.86, SOYPR = 115.34, SOYWA = 125.10 /

 SCALAR   REVENUE   / 5000000 /

 VARIABLES

     MIX(ACTIVITIES)          Mix of production activities
     TCOST                    Value of objective function
     POSITIVE VARIABLE MIX

 EQUATIONS

     TOTALR                   Revenue Calculation & Constraint
     CAP(RESOURCES)           Capacity Constraints
     TOTALC                   Accounting:  Costs;

 TOTALR..          SUM(ACTIVITIES, RECEIPTS(ACTIVITIES) * MIX(ACTIVITIES)) =G= REVENUE;
 CAP(RESOURCES).. SUM(ACTIVITIES, LANDUSE(ACTIVITIES, RESOURCES) * MIX(ACTIVITIES)) =L=
                  + RHS(RESOURCES);

 TOTALC..          TCOST =E= SUM(ACTIVITIES, COSTS(ACTIVITIES) * MIX(ACTIVITIES));
 MODEL SOYCNV Conventional Till Cost Problem / ALL /; SOLVE SOYCNV MINIMIZING TCOST USING LP;
```

Figure A.4. Linear programming model for conventional tillage soybeans.

```
$TITLE MLRA 134 WHEAT MODEL - CONSERVATION TILLAGE
$OFFUPPER

SETS
      ACTIVITIES Each crop as produced on a specific soil type
         / WHEATAD, WHEATBI, WHEATCA, WHEATCL, WHEATCV, WHEATFA, WHEATGR,
           WHEATLX, WHEATLO, WHEATME, WHEATPR, WHEATWA /
      RESOURCES
         / ADLER, BIRDS, CALLOWAY, COLLINS, CONVENT, FALAYA, GRENADA,
           LEXINGTON, LORRING, MEMPHIS, PROV, WAVERLY /

TABLE LANDUSE(ACTIVITIES, RESOURCES)  Land use by crop and soil type

          ADLER BIRDS CALLOWAY COLLINS CONVENT FALAYA GRENADA LEXINGTON LORRING MEMPHIS PROV WAVERLY
WHEATAD     1     0      0        0       0       0      0        0         0       0      0     0
WHEATBI     0     1      0        0       0       0      0        0         0       0      0     0
WHEATCA     0     0      1        0       0       0      0        0         0       0      0     0
WHEATCL     0     0      0        1       0       0      0        0         0       0      0     0
WHEATCV     0     0      0        0       1       0      0        0         0       0      0     0
WHEATFA     0     0      0        0       0       1      0        0         0       0      0     0
WHEATGR     0     0      0        0       0       0      1        0         0       0      0     0
WHEATLX     0     0      0        0       0       0      0        1         0       0      0     0
WHEATLO     0     0      0        0       0       0      0        0         1       0      0     0
WHEATME     0     0      0        0       0       0      0        0         0       1      0     0
WHEATPR     0     0      0        0       0       0      0        0         0       0      1     0
WHEATWA     0     0      0        0       0       0      0        0         0       0      0     1;

PARAMETERS

 RECEIPTS(ACTIVITIES)  Total Receipts (Dollars Per Acre)
  / WHEATAD = 180.20, WHEATBI = 000.00, WHEATCA = 166.60, WHEATCL = 180.20,
    WHEATCV = 125.80, WHEATFA = 119.00, WHEATGR = 176.80, WHEATLX = 187.00,
    WHEATLO = 197.20, WHEATME = 176.80, WHEATPR = 146.20, WHEATWA = 000.00 /

 RHS(RESOURCES)
  / ADLER = 8881, BIRDS = 5609, CALLOWAY = 38327, COLLINS = 59360,
    CONVENT = 3739, FALAYA = 78991, GRENADA = 73382, LEXINGTON = 7011,
    LORRING = 108903, MEMPHIS = 28511, PROV = 18229, WAVERLY = 36457 /

 COSTS(ACTIVITIES)  Costs (Dollars Per Acre)
  / WHEATAD = 114.31, WHEATBI = 129.28, WHEATCA = 134.61, WHEATCL = 129.56,
    WHEATCV = 128.70, WHEATFA = 131.68, WHEATGR = 134.93, WHEATLX = 116.73,
    WHEATLO = 131.89, WHEATME = 136.43, WHEATPR = 114.06, WHEATWA = 128.51 /

 SCALAR   REVENUE   / 5000000 /

 VARIABLES

     MIX(ACTIVITIES)           Mix of production activities
     TCOST                     Value of objective function
     POSITIVE VARIABLE MIX

 EQUATIONS

     TOTALR                    Revenue Calculation & Constraint
     CAP(RESOURCES)            Capacity Constraints
     TOTALC                    Accounting:  Costs;

 TOTALR..          SUM(ACTIVITIES, RECEIPTS(ACTIVITIES) * MIX(ACTIVITIES)) =G= REVENUE;
 CAP(RESOURCES).. SUM(ACTIVITIES, LANDUSE(ACTIVITIES, RESOURCES) * MIX(ACTIVITIES)) =L=
                  + RHS(RESOURCES);

 TOTALC..          TCOST =E= SUM(ACTIVITIES, COSTS(ACTIVITIES) * MIX(ACTIVITIES));
 MODEL WHTCNS No Till Cost Problem / ALL /; SOLVE WHTCNS MINIMIZING TCOST USING LP;
```

Figure A.5. Linear programming model for conservation wheat.

```
$TITLE MLRA 134 WHEAT MODEL - CONVENTIONAL TILLAGE
$OFFUPPER

SETS
      ACTIVITIES Each crop as produced on a specific soil type
         / WHEATAD, WHEATBI, WHEATCA, WHEATCL, WHEATCV, WHEATFA, WHEATGR,
           WHEATLX, WHEATLO, WHEATME, WHEATPR, WHEATWA /
      RESOURCES
         / ADLER, BIRDS, CALLOWAY, COLLINS, CONVENT, FALAYA, GRENADA,
           LEXINGTON, LORRING, MEMPHIS, PROV, WAVERLY /

TABLE LANDUSE(ACTIVITIES, RESOURCES)  Land use by crop and soil type

          ADLER BIRDS CALLOWAY COLLINS CONVENT FALAYA GRENADA LEXINGTON LORRING MEMPHIS PROV WAVERLY
WHEATAD    1     0     0        0       0       0      0       0         0       0       0    0
WHEATBI    0     1     0        0       0       0      0       0         0       0       0    0
WHEATCA    0     0     1        0       0       0      0       0         0       0       0    0
WHEATCL    0     0     0        1       0       0      0       0         0       0       0    0
WHEATCV    0     0     0        0       1       0      0       0         0       0       0    0
WHEATFA    0     0     0        0       0       1      0       0         0       0       0    0
WHEATGR    0     0     0        0       0       0      1       0         0       0       0    0
WHEATLX    0     0     0        0       0       0      0       1         0       0       0    0
WHEATLO    0     0     0        0       0       0      0       0         1       0       0    0
WHEATME    0     0     0        0       0       0      0       0         0       1       0    0
WHEATPR    0     0     0        0       0       0      0       0         0       0       1    0
WHEATWA    0     0     0        0       0       0      0       0         0       0       0    1;

PARAMETERS

 RECEIPTS(ACTIVITIES)  Total Receipts (Dollars Per Acre)
  / WHEATAD = 176.80, WHEATBI = 000.00, WHEATCA = 170.00, WHEATCL = 176.80,
    WHEATCV = 122.40, WHEATFA = 122.40, WHEATGR = 176.80, WHEATLX = 180.20,
    WHEATLO = 190.40, WHEATME = 183.60, WHEATPR = 142.80, WHEATWA = 000.00 /

 RHS(RESOURCES)
  / ADLER = 8881, BIRDS = 5609, CALLOWAY = 38327, COLLINS = 59360,
    CONVENT = 3739, FALAYA = 78991, GRENADA = 73382, LEXINGTON = 7011,
    LORRING = 108903, MEMPHIS = 28511, PROV = 18229, WAVERLY = 36457 /

 COSTS(ACTIVITIES)  Costs (Dollars Per Acre)
  / WHEATAD = 101.57, WHEATBI = 116.54, WHEATCA = 121.87, WHEATCL = 116.82,
    WHEATCV = 115.96, WHEATFA = 118.94, WHEATGR = 122.19, WHEATLX = 103.99,
    WHEATLO = 119.15, WHEATME = 123.69, WHEATPR = 101.32, WHEATWA = 115.77 /

 SCALAR   REVENUE    / 5000000 /

 VARIABLES

     MIX(ACTIVITIES)           Mix of production activities
     TCOST                     Value of objective function
     POSITIVE VARIABLE MIX

 EQUATIONS

     TOTALR                    Revenue Calculation & Constraint
     CAP(RESOURCES)            Capacity Constraints
     TOTALC                    Accounting:  Costs;

 TOTALR..          SUM(ACTIVITIES, RECEIPTS(ACTIVITIES) * MIX(ACTIVITIES)) =G= REVENUE;
 CAP(RESOURCES)..  SUM(ACTIVITIES, LANDUSE(ACTIVITIES, RESOURCES) * MIX(ACTIVITIES)) =L=
                   + RHS(RESOURCES);

 TOTALC..          TCOST =E= SUM(ACTIVITIES, COSTS(ACTIVITIES) * MIX(ACTIVITIES));
 MODEL WHTCNV Conventional Till Cost Problem / ALL /; SOLVE WHTCNV MINIMIZING TCOST USING LP;
```

Figure A.6. Linear programming model for conventional tillage wheat.

VITA

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