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A Simulation of the Economic Effects of Alternative Soil Types and Nitrogen Sources on Nitrate Leaching on Irrigated Agriculture in Utah

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A SIMULATION OF THE ECONOMIC EFFECTS OF ALTERNATIVE SOIL TYPES AND NITROGEN SOURCES ON NITRATE LEACHING ON IRRIGATED AGRICULTURE IN UTAH

by

Gilbert D. Miller

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of the requirements for the degree

of

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Gilbert D. Miller

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ABSTRACT

A Simulation of the Economic Effects of Alternative Soil Types and Nitrogen Sources on Nitrate Leaching on Irrigated Agriculture in Utah

by

Gilbert D. Miller, Doctor of Philosophy

Utah State University, 1991

Major Professor: Jay C. Andersen
Department: Economics

The economic impact of reducing the amount of nitrate leached out of the root zone under irrigation in the arid West was examined. A general introduction into the nature of the problem and a review of the literature was provided in chapter I. In chapter II the economic incentives of irrigation management were evaluated under the assumptions of both profit-maximizing and utility-maximizing (in reducing cost and effort expended in irrigation) decision-making criteria. The results indicate that there is a coincidence of interests of the farmer and the environment. Both behaviors result in less nitrate leaching than less profitable or less utility-producing irrigating practices. In chapter III the economic impact of reducing the amount of nitrate leached out of the root zone under irrigation with various nitrogen sources and application methods was examined. The economic incentives of nitrogen management were evaluated under the assumption of profit-maximizing behavior. The results indicate that there is a coincidence of interests for irrigators who respond to economic incentives and environmentalists who wish to reduce nitrate residuals in irrigation drainage and the groundwater. Profit-maximizing behavior results in less nitrate leaching than less profitable irrigating practices when salt balance is not a major concern.

(90 pages)

CHAPTER I

GENERAL INTRODUCTION AND LITERATURE REVIEW

This study deals with the effects of nitrogen fertilizer and irrigation on nitrate contamination of groundwater. The journal format option is used to describe the study. The general introduction and literature review is used to detail background of the study and tie the two articles, chapters II and III, together. A summary follows chapter III to integrate the results reported in the two articles. The literature review is built around three areas: a brief outline of the health effects of nitrates, the economics of externalites, and the physical interactions that affect nitrate leaching.

Health Effects

Nitrate contaminated groundwater has been shown to create health problems in humans and livestock. Methemoglobinemia is the primary disease associated with nitrate. Nitrate, while not metabolized by mammals, is metabolized to nitrite by bacteria found in saliva and digestive systems of mammals. Nitrite reacts with hemoglobin to form methemoglobin which cannot transport oxygen (USEPA 1987). Death can result when sufficient amounts of hemoglobin are transformed to methemoglobin. Infants and pregnant women are particularly sensitive to the induction of clinical methemoglobinemia (USEPA 1987). Nitrite in horses not only causes methemoglobinemia, but "vasodilation which results in cardiovascular collapse and shock" (USEPA 1987, p. 6). The evidence that nitrate and nitrite cause cancer is inconclusive. Nitrate and nitrite ingested with nitrosable compounds may form N-nitroso compounds, many of which are known to be carcinogenic (Shank and

Magee). Fortunately, nitrate is readily excreted from the body with no bioaccumulation of nitrate or nitrite in any tissue (USEPA 1985).

Groundwater containing nitrate is one source of ingestible nitrate. Ground water can be contaminated by nitrate from a number of sources including septic systems, feedlots, other concentrated livestock and poultry operations, organic matter, and commercial fertilizers (Newcomer; Kolaja et al.). Point sources are sources such as septic systems and feedlots where an individual or firm responsible for the nitrate being in the groundwater can be identified (Tietenberg). Nonpoint sources are sources in which the individuals or firms responsible are not identifiable or the contribution of each agent to nitrate level in the groundwater is not known.

Economics of Externalities

Both point and nonpoint sources generate externalities. Just et al. (p. 269) define an externality "as the case where an action of one economic agent affects the utility or production possibilities of another in a way that is not reflected in the marketplace." What this means for this study is that farmers do not consider the effects on others when they make their decisions on any actions which produce nitrates in groundwater. This study deals with nonpoint sources due to applying commercial nitrogen fertilizers and irrigation to cropland.

Farmers (firms) maximize profits where marginal revenue equals margin cost (Stigler). Applying this to the use of nitrogen fertilizers, the farmer has the incentive to apply fertilizer to the point where the value of the marginal product (VMP) of the last unit of fertilizer applied is equal to the cost of that unit (MFC marginal factor cost) of fertilizer. Since this fails to take into account the cost imposed on others, the incentive for the farmer would be to apply more than the amount that would be optimal for society. The optimal amount for society is the VMP equal to the MFC plus the marginal social cost (MSC) (Just et al.). The social optimal fertilizer application rate is thus, dependent upon not only the MFC but also the MSC.

Once the MSC has been determined, policy instruments can be used to reduce the external costs (the negative externalities imposed). Methods for correcting external costs include taxes or subsidies on outputs or inputs, the establishment of standards, or assignment of property rights (Just et al.). In the literature review these policy instruments were evaluated on their impacts on nitrate leaching and their effects on net farm income, income distribution, cropping patterns, and external trading patterns.

Tinbergen suggests that economic policy is divided into four parts. Target variables are the things that the policymaker is interested in "purposefully" (Fox et al.) influencing, for example nitrates in groundwater. Policy instruments are variables that affect target variables that are under the control of policymakers, at least in theory. Side-effect variables are things that are affected by the policy instruments that are not of concern to the policymaker; for example, an environmental policymaker may not be concerned with the effects of a policy instrument on farm income. Exogenous variables are uncontrollable factors that affect the target variable and the side-effect variables.

Nitrate leaching is the target variable in the study. Returns to management or net farm income, income distribution, cropping patterns, and external trade patterns are the side-effect variables. Subsidies, taxes, standards, and property rights are the policy variables or instruments. Weather and soil characteristics are uncontrollable factors or exogenous variables.

Briassoulis (p. 24) stated, "A complete integrated model consists (or should consist) of four major interrelated components: an economic, an environmental, a policy (or decisionmaking), and an exogenous component." The variables described above fit Briassoulis's definition of a complete integrated model. She suggests that "spatial aspects of an environmental issue" be considered in defining an appropriate region. The appropriate region for extending the results of this study is the irrigated farmland in the arid West where salt balance can be maintained without extensive leaching.

We begin the evaluation of the policy instruments with an evaluation of subsidies. Baumol and Oates prefer taxes to subsidies for two reasons. First, subsidies may keep alive a polluting enterprise that would otherwise be unprofitable; secondly, it is difficult to determine which pollution level is the appropriate starting point from which to measure improvements for subsidy payments. The nonpoint source nature of nitrate leaching associated with fertilizer use causes other problems in using subsidies to achieve water quality standards. Paying each polluter for their marginal contribution to the reduction of nitrate is not possible because of lack of measurability. A free rider problem may also exist because it is impossible to identify the individuals responsible for the reduction in nitrate leaching. Thus, some individuals may receive a subsidy without contributing to the reduction. Subsidies may be used to build water treatment facilities to remove nitrate from drainage water or groundwater (Horner; Houck et al.).

A tax on the product that produces the externality was first proposed by Pigou as a method of achieving the optimal level of production. A per-unit tax on the product equal to the difference between the MSC and the MPC (marginal private cost), thus making the MPC equal to the MSC, may reduce output to the socially optimal level (Just et al.). Hanley reporting work done in England found a 30% decrease in the price of wheat resulted in only a 1.9% reduction in nitrate applications with an accompanying "loss of farm income of £81.10/hectare" (p. 139). Huang and Lantin reported that a "Corn Sales Tax" sufficient to achieve the optimal fertilizer application level in their "Iowa Case Study" resulted in "an income loss of $601" per acre. Using Woodruff's nitrogen response equation, nitrogen priced at $0.26 per pound and the price of corn at $1.24 per bushel, soil nitrogen level is 400 pounds per acre where VMP = MFC with a total revenue of $331.08. To reduce the soil nitrogen to 300 pounds per acre, the price of corn would need to drop to $0.49 per bushel. A tax of $0.74 per bushel is needed so that farmers receive $0.49 per bushel for corn. This would reduce total revenue to $120.54. The revenue that farmers receive after the tax is far below the variable costs of production reported for 1989 of $1.12 per bushel (USDA-ERS 1991) for the Lake States and Corn Belt. Edelman (1987, p. 2) states, "Arithmetic shows that it is profitable to add nitrogen as long as corn is above 25 cents per bushel. Farmers will liquidate and exit farming . . . " before a tax would reduce nitrogen applications to the desired rate. Besides corn, an optimal tax would need to be found for each crop produced, for each area of production based on the uncontrollable factor such as soil type, weather conditions, and other environmental conditions (Abrams and Barr). This would cause major changes in cropping patterns. Changes in cropping patterns would cause changes in export markets and livestock industry (Abrams and Barr). The conclusion is clear that a tax on agricultural products has significant shortcomings as a policy for reducing nitrates in groundwater.

A tax on the polluting input (nitrogen) has been suggested as a policy instrument to reduce the amount of nitrate in groundwater (Huang and Lantin; Hanley). "A crucial parameter in all price incentive based policies aimed at controlling nitrogen use is the price elasticity of demand for nitrogen fertilisers," states Hanley (p. 138). He reports price elasticities for nitrogen fertilizers from several European countries to be between -0.08 and -1.20 with most being greater than -0.6. "Given that demand for nitrogen is price-inelastic, then quite high tax rates would need to be introduced to achieve significant reductions in nitrogen use," concludes Hanley (p. 138). In Denmark, a tax of 150% was required to obtain a 30% reduction in nitrogen fertilizer use as calculated by Dubgraad (Hanley). England estimated that a 100% tax on nitrogen fertilizer would result in only an 8.6% reduction in nitrogen fertilizer applied to winter wheat in the UK (Hanley). Huang and Lantin report that a tax on nitrogen sufficient to reduce the application rate to the level of nitrogen removed from the field in crops resulted in a cost per pound of nitrogen of $0.29 to $1.18 as measured by reductions in net farm income, depending on crop rotation. Edelman (1986) concludes that a large tax on nitrogen would need to be imposed before the amount of nitrogen applied to corn in Iowa would be reduced.

Quite differently Abrams and Barr found that in Illinois, tax rates much lower than those cited above were needed to meet drinking water quality standards for nitrates (10 mg/liter). Taxes ranged from $0.00 to $0.02 per pound of nitrogen depending on the region of the state. They reported that no change in cropping patterns were needed to meet drinking water standards for nitrate. Tightening the standard from 10 to 5 mg/liter resulted in tax rates of $0.02 to $0.15 per pound of nitrogen. Meeting the higher standard caused the cropping pattern to change. Less corn and hay-silage were grown, but more cropland pasture was raised and wheat was introduced. The 5 mg/liter standard resulted in changes in the feed fed to livestock. The amount of wheat, barley, and sorghum fed increased, while the amount of corn, soybeans, and cottonseed fed fell. Regional effects of the 5 mg/liter standard on net farm income were profound. Some regions had increases in net farm income as a result of the higher standard, some were little changed, while others had substantial losses. Conclusions drawn from Abrams and Barr's work include the following: (1) effects of meeting drinking water standards for nitrate using input taxes may require much lower taxes than some have suggested; (2) the income effect of input taxes will vary by regional, environmental, and economic characteristics; (3) input taxes may have substantial effects on cropping patterns; (4) cropping patterns may have profound effects on livestock industries; and (5) increasing supply prices may affect consumer prices and export trade between regions or nations.

Taylor analyzed the use of permits or rights to apply nitrogen fertilizers. He proposed that a public agency determine the desired water quality and associated number of permits to achieve the desired water quality. The agency is then to have individual farmers reveal their demand curve for nitrogen fertilizer, and then add these up to determine the market demand. He would then set the price of permits to clear the number of permits that are available and sell the permits to the farmers. Farmers are then free to use or sell any permit that they own. This is to be done annually. In his analysis, the marginal cost of control decreases as the desired reduction increases. This is in contrast with results of a study by Hartley, which indicated that the marginal cost increases as the reduction level increases (Hanley). Taylor's distribution scheme removes income from the agricultural sector. Hanley suggests that the transfer of money out of the agricultural sector can be eliminated by giving the permits to the farmers and letting them trade the permits. Income distribution within the sector would change, but the income would still be in the agricultural sector.

Rather than taxes on outputs or inputs, a tax or emissions charge has been proposed as a method of correcting externalities (Baumol and Oates; Tietenberg; Just et al.). Baumol and Oates suggest that an iterative process can be used to achieve the desired standard where the tax on each unit emitted is equal to the value of damage caused by the marginal unit of effluent. This would allow the controlling agency to avoid the high cost of predetermining the optimal tax before implementing the corrective policy. Horner asserts that an iterative method of tax implementation may lead to a suboptimal level of investment in pollution abatement technology because of fixed cost associated with any given level of technology initially employed. Effluent charges for nonpoint source pollution is not a workable policy option, because individual polluters are not identifiable and emissions are not easily determined (Stevens). Segerson proposes a tax on ambient levels above some standard because they are more readily determined than emission levels. To overcome the inherent free rider problem she suggests that each farmer would pay a fee equal to the value of the marginal damage. Each farmer has the correct marginal incentive to take the appropriate action to reduce pollution to the optimal level. Under Segerson's proposal, if $100 damage was done $100 times, the number of farmers in the appropriate region would be collected by the governing agency. This is a substantial redistribution of income from farmers to the taxing agency.

Limiting the amount of nitrogen fertilizer that can be applied has been proposed as a method of reducing nitrates in groundwater (Huang and Lantin; Lambert; and Edelman 1987). Lambert (p. 242) found that farmers would "prefer a quantity restriction to taxes under equal levels of control." Huang and Lantin (p. 9) demonstrated that "the Limiting Nitrogen Fertilizer Use has the lowest cost to the farmer" of the policy alternatives they studied. "The regulation option may be the most effective method of controlling excess fertilizer use if policy makers decide that safe groundwater requires a lower amount of fertilizer than farmers would apply to maximize their profits" concludes Edelman (1987, p. 2).

Radosevich reported that water rights often inhibit farmers from adopting irrigation technologies that could improve water quality. The appropriated water right developed to solve the water scarcity problems of the 1800s is contributing to the water quality problems of today. "At the heart of the appropriation doctrine . . . is the concept of beneficial use" (p. 47). He suggests that "A major change in the nature of a water right that would serve to protect the interests of the right and later water users would be to add the element of water quality" (p. 47) to the concept of beneficial use.

> In so doing, the right holder would have the same assurance and likewise liability in the use of diverted water within the priority system for quality purposes as he now has for quantity flows. This change would be instrumental in encouraging practices to treat or dispose of highly saline waste waters and encourage the proper application of water on the farm (p. 48).

He also advocates the transfer of water rights through water markets, in which right holders could rent, lease, or sell water. He asserts that water markets would encourage right holders to employ water-saving technologies and management techniques so that they could market the surplus water they had created.

Physical Interactions

Best Management Practices (BMP) have been recommended as a method of reducing nitrate pollution of groundwater (Saliba; Keeney; Newcomer; Randall). Since the amount of NO_3^- that leaches from the soil depends on the amount of water that moves through the soil, soil characteristics are important in determining the BMP for a given site. This was demonstrated in research reported by Sheppard and Bates. Given the same fertilizer treatments, Sheppard and Bates found that the amount of residual nitrate remaining in the soil profile in the spring on three southern Ontario soils was greatly influenced by soil type. They found that it was "unlikely" that there would be enough residual nitrogen in the soil by spring to have any "residual effects" on crop production the next growing season "on course-textured soils." They conclude that leaching was the cause of the loss of residual nitrogen over the nongrowing season "especially on the sandy loam and silt loam sites" (p. 539). The nitrate "contents in the clay loam site remained highly dependent on the level of applied N" being "almost unaltered between fall and spring sampling" (p. 539). Thus, the identical management had different environmental consequences. Given that each soil type will respond differently to each of the proposed management practices, the discussion of BMP is begun.

Soil testing for nitrate is universally recommended as a BMP (James and Topper; Randall; IFIA; Keeney). Soil testing allows the farmer to adjust application rates to provide sufficient nitrogen to meet crop yield goals or to maintain a given soil fertility level (James and Topper). James and Topper (p. 3) suggest that the sufficiency approach is the better approach to soil fertility because "generally the sufficiency approach maximizes economic returns on fertilizer investment . . . ." The other authors cited implicit use of the sufficiency approach in their discussions for both economic and environmental reasons. James and Topper provide for corrections to nitrogen recommendations based on crop history, crop residue and manure management, and soil characteristics. There is some disagreement on the timing of soil testing. Winsor (p. 18) states, "Fall is the ideal time to soil test. By identifying existing nitrate levels and counting credits, you'll be able to assess plant food needs long before spring." Randall (p. 46) states that "Spring sampling, however, will provide a more reliable estimate of carryover NO_3^- than fall sampling because of potential losses of NO_3^- during the late fall through early spring period."

Once the amount of nitrogen to be applied has been determined, the next step is to select the form of nitrogen to apply. It has been suggested that nitrogen fertilizers that supply nitrogen in the NH_4^+ form or that are transformed into NH_4^+ form are preferable to nitrate forms because they are immobile in the soil complex (Randall; Tisdale et al.). The use of nitrification inhibitors (NI) has been proposed as a method of reducing nitrate leaching (Walters and Malzer). NI are "materials that delay the transformation of ammonium to nitrate" (James and Topper, p. 5). Delaying the transformation of ammonium to nitrate means that the nitrogen applied as fertilizer would be immobile longer but still be in a form that plants can use; thus, more of it should be taken up by plants and, therefore, be unavailable to leaching beyond the root zone. Walters and Malzer found that (for fertilizer application greater than plants used) "there was no reduction in the quantity of N leached over the long run" (p. 125) using NI. James and Topper suggest that NI would be most useful on coarse-textured soils where control of soil moisture under irrigation is difficult. "Since the behavior of nitrification inhibitors is not fully predictable, it is not possible to give a specific recommendation on the use of these materials" (James and Topper, p. 6). James and Topper are less concerned about the form of the nitrogen fertilizer applied in the arid West because nitrification will transform 80% to 90% of ammonium into nitrate within a month of application. They conclude that management practices should treat all forms of nitrogen as if they were nitrate because they all are nitrified in a relatively short period of time.

When to apply the nitrogen fertilizer becomes the next question. A summary of fall versus spring applications provided by Keeney shows that there is no clear-cut answer to which time is best. Keeney (p. 595) concludes "this divergence of findings is likely due to year-to-year climatic differences, and to the many other factors which may affect plant yields." Fall applications of nitrogen fertilizers may be appropriate for those areas where climatic conditions are such that there is little likelihood of the fertilizer being lost during the nongrowing season. Segarra et al. suggest that there may be an optimal nitrogen carryover for irrigated crops in some arid regions, implying that what is there in the fall will still be there the next growing season.

The timing of application may include more than one application per growing season, known as split applications. Randall (p. 46) outlines the logic of split applications as follows, less "time between fertilizer application and maximum crop uptake reduces the probability of loss due to either leaching or denitrification." He relates that coarse-textured highly permeable soils will show more benefit from split applications than will fine-textured soils. Gerwing et al., reporting on their study of split applications of urea on a sandy loam soils, concluded that split applications lead to a more uniform distribution of nitrate throughout the soil profile and a greater opportunity for plant utilization of the fertilizer than single applications. When nitrogen fertilizer applications were near the amounts needed to achieve historically average yields, the work of Gerwing et al. showed an increase in the amount of nitrogen fertilizer recovered in the plants which reduced nitrate leaching from that of a single application of the same amount of fertilizer. Higher N application rates did not demonstrate these same results, in fact, nitrate leaching increased. Jokela and Randall suggested that under the conditions of their study, where 8L means eight leaf "the delay of fertilizer N application to the 8L stage, generally considered a best management practice, may have actually increased the potential for leaching of NO_3^- beyond the root zone and eventually into groundwater" (p. 720). Randall believes that the excess nitrogen of late applications increases the likelihood that it will be lost because of the shorter time that it is available to plants before harvest. Split applications of N should be deep enough so that there is sufficient moisture to make the fertilizer available to plants (Randall).

Split applications of N fertilizers on row crops are usually done by sidedressing which must occur before the plants develop sufficiently to close the rows (Keeney). Hergert (p. 277) proposes "Fertigation or N fertilizer application with irrigation water" as a method of splitting N fertilizer applications. Newcomer suggests the plants can be spoon fed throughout the growing season using fertigation. Timmons and Dylla reported that fertigation with two-inch irrigations reduced the amount of nitrate leached. They suggest a corn management system combining partial replenishment irrigation with periodic application of N fertilizer in irrigation water to maintain yields and minimize water and nitrate percolation.

Irrigation management has been shown to be an important tool in reducing nitrate leaching (Hergert; Duke et al.; Ludwick et al.; Smika et al.; Timmons and Dylla). Duke et al., using an irrigation scheduling program developed for the USDA, demonstrated that irrigation scheduling (determining the best amount and the timing of irrigation) can be used to minimize leaching losses. Irrigation management has a significant influence on soil nitrate placement in the soil profile (Ludwick). Pratt showed that for any given level of N fertilizer application, the amount of nitrate leached increased with increases in the amount of water that percolated through the root zone. Managing irrigations so as to reduce the amount of deep percolation will reduce nitrate leaching. Uniformity of application is, therefore, important in controlling nitrate leaching beyond the root zone.

Groundwater Amelioration Methods

Six basic groundwater amelioration methods have been proposed to reduce nitrate levels in groundwater: (1) blending nitrate-bearing groundwater with noncontaminated water sources (Houck et al.), (2) nitrate removal by ion exchange (Guter; Houck et al.), (3) nitrate removal by reverse osmosis (Eisenberg and Middlebrooks), (4) biological denitrification of nitrate-contaminated groundwater in containment ponds (Horner), (5) in reactor facilities (Dahab), and (6) in shallow aquifers (Adelman and Spalding).

Public water systems that have more than one water source may be able to blend water which exceeds the nitrate standard with water that is below the standard to achieve the desired quality at little expense. They may be able to develop new sources of high quality water or organize a regional water system at lower cost than constructing treatment facilities (Houck et al.). Private water supplies are less amenable to blending because of the expense of monitoring nitrate levels in the water and developing alternative water sources. Contamination by nitrates is usually localized. Therefore, drilling a new well may be a viable alternative to treating nitrate laden groundwater (Houck et al.).

The only water amelioration facilities built especially to remove nitrates from public water supplies have been ion exchange facilities (Houck et al.). Nitrate (an anion) is removed by exchanging nitrate in the water with another anion in a resin bed through which the water passes. "Resin beds are made up of millions of tiny, spherical beads . . . on which exchange sites are available" (Houck et al., p. 587). Houck et al. (p. 588) describe the exchange process as having four parts: (1) "The ion exchange resin is fully recharged"; (2) "The ion exchange resin is exchanging chloride ions for sulfate and nitrate ions, releasing chloride ions into the water and retaining sulfate and nitrate"; (3) "The exchange sites have been used up and the resin is said to be 'exhausted' or 'spent'"; and (4) "The resin is 'regenerated' by passing a strong salt water (brine) solution of sodium chloride (NaCl) through the resin bed. The very high relative chloride concentration displaces the sulfate and nitrate ions from the exchange sites on the resin beads." The brine bearing the nitrate and sulfate ions is then flushed from the resin bed. Disposal of the brine in an environmentally safe way poses a problem to be dealt with. Guter reported that the total cost of treating nitrate bearing well water (15.2 mg/l) to under 7 mg/l for blended water for a million gallon per day facility operating at full capacity was $0.25 per 1,000 gallons. The total cost per 1000 gallons of blended water using a 100,000 gallon per day facility was estimated to be $0.50.

Another method of removing nitrates from water for drinking purposes is reverse osmosis. "Reverse osmosis is a process in which water is forced through a semipermeable membrane that will not pass dissolved substances" like minerals, radionuclides, nitrate, and other ions (Houck et al., p. 628). The effectiveness of reverse osmosis is influenced by pressure of the system, the characteristics of the membrane, and the materials in the water (Eisenberg and Middlebrooks). Reverse osmosis has been used to remove salts from sea water at various locations and from the Colorado River for years. However, no public water treatment facilities have been built exclusively for removing nitrates (Houck et al.). The yields for reverse osmosis to date have been less than the yields using ion exchange. There are a number of small reverse osmosis systems available for home use (Consumer Reports, CR). These small home units operate at water pressures above 45 pound per square inch. They have a yield of only 10% to 25% (CR) compared with yields of 75% for high pressure desalination units (Eisenberg and Middlebrooks). The cost for a family of four using a reverse osmosis for purifying water for drinking and cooking at a rate of two gallons per person per day can range between $100 and $360 per 1,000 gallons depending on the unit used.

Biological denitrification of drainage water from irrigated land has been studied as a way to reduce irrigated agriculture's impact on the environment (Horner). Biological denitrification uses microorganisms to convert "nitrates in water into nitrogen gas (N_2) with smaller amounts of nitrous oxide or nitric oxide" (Dahab, p. 26). Municipalities and industry have used biological denitrification extensively to remove nitrates from waste water (Dahab). The Horner study using a linear programming model shows that, for the San Luis Unit of the Central Valley Project in the San Joaquin Valley of California, an effluent charge on the nitrate each producer contributed to the drainage system was more cost effective than building treatment facilities. Using the cost equation used by Horner, adjusted for inflation by the Producers Price Index (PPI), to treat approximately 45,000 acre feet of water of the same quality as reported by Guter, the cost was $0.29 per 1,000 gallons. The cost of the drainage collection system was not included in the treatment cost.

Dahab proposes that biological denitrification be used for the treatment of drinking water not just waste water. He made a reactor with plastic beads to service as the support for the biological agents. Dahab used acetic acid as the carbon source. He concluded that "biodenitrification can be carried out successfully" (p. 33). The process needs further study. No cost estimates were given.

Like Dahab's experimental work with biodenitrification, Adelman and Spalding studied injecting ethanol into the soil to enhance denitrification in the soil to reduce the amount of nitrates that leach into groundwater. They chose the shallow aquifers of the Sandhills Region of Nebraska as the study area. Using field data and a simulation model, they studied the environmental and economic risks associated with groundwater quality and nitrates over a 40-year period. Adelman and Spalding (p. 32) concluded, "In terms of risk and economic return, comparison of farm management practices with and without ethanol injection for the area studied reveals that those practices with injection are always more feasible than those without." They too suggest more study.

Evaluating BMP Using Nitrogen-Soil-Plant-Water Models

> The questions being asked about N emissions from cropland and their environmental impacts are so broad and complex that even knowledgeable agronomists rely heavily on experience and intuition. The factors and processes contributing to or affecting N loss are so numerous and interactive that without resorting to some kind of modeling it would be extremely difficult to integrate and synthesize the large body of existing information and data, let alone those that are unknown. . . . it should clearly be recognized that a model is only a substitute for the real system. The one and only complete model of a natural system is the system itself. The real world complexities are simplified for modeling. . . . problems related to N are exceedingly complex and difficult to answer, we should take advantage of combining the power of the human mind and the computer. (Tanji, p. 767)

> Simulation models are used to estimate the effects of existing and planned practices, and thus minimize the uncertainty associated with the effects of management practices on runoff and groundwater quality. The 'optimal' or cost effective set of BMPs can then be selected for controlling the individual pollutants or aggregates of concern. . . . a model must be capable of simulating reasonable management alternatives to be useful for economic analysis of BMPs. . . . abatement of agricultural nonpoint pollution requires a focus on farm fields, the scale at which agricultural activities are performed. (Crowder, p. 314)

Many models have been developed for the study of nitrogen problems. Many of them have been developed for specific sites and are, therefore, not appropriate for more general applications (Tanji). Crowder reviewed eight models that have been used for evaluating the effects of management practices on agricultural nonpoint pollution. None of these models were of use in this study because they only gave relative ranking of management practices or were developed for runoff problems, not groundwater problems which is the focus of this study.

Two models were selected for further review: NITWAT, a Nitrogen and Water Management Model (McIsaac et al.); and NTRM, a Soil-Crop Simulation Model for Nitrogen, Tillage, and Crop-Residue Management (Shaffer and Pierce). Both models are deterministic, therefore, the stochastic effect must be simulated by changing soil, weather, irrigation, or initial conditions used for various simulations.

NITWAT was developed to provide "a means of examining on a 'macro' scale the interaction of the major processes affecting nitrogen uptake and leaching in the sandy soil environment" (McIsaac et al., p. 3). The model calculates soil moisture movement, net nitrogen mineralization, movement of nitrate, ammonium, and urea, crop water use and crop nitrogen uptake given user supplied soil, crop, and weather data. NITWAT had three shortcomings that limited its usefulness for this inquiry and planned future study: (1) it is limited to sandy soils, therefore, an evaluation of BMPs over soil type was not possible; (2) ammonium nitrate was limited to a single application, therefore, split applications could not be evaluated as a BMP; (3) corn was the only crop on which BMPs could be evaluated.

NTRM was developed to integrate management practices related to tillage, crop-residues, and nitrogen fertilizers (Shaffer et al.). NTRM is more flexible than NITWAT in the problems to which it can be applied. A wide range of soils can be modeled using NTRM by adjusting soil parameters to reflect those of the soil of interest to the researcher. A maximum of 25 fertilizer applications can be simulated. NTRM can also be used to model salt accumulation and movement. This can be important in modeling irrigated agricultural practices in areas where maintaining salt balance is a problem in maintaining crop yields. Crops other than corn can be modeled using NTRM. This is important in evaluating the effects of cropping patterns on nonpoint pollution problems. NTRM was selected to be used in this study because it models the management practices that are of interest to this study and planned future research better than other models currently available.

Mathematical Representation of Farmer Incentives under Selected Control Measures

Incentives for profit maximizing farmers under perfect competition in both product and factor markets, where a single product was produced using two factors of production, was the focus of the study. Corn silage was the product of interest for this study and nitrogen fertilizer and irrigation water were the inputs of concern. The decisionmaker (farmer) faces the problem of maximizing profits, that is maximizing the difference between total revenues and total cost. The mathematical statement of the problem is

$$(1) \qquad Max\ \Pi = PY - W_N N - W_I I - FC$$

subject to:

$$(2) \qquad Y = f(N, I)$$

where P is the price of corn silage; Y is the units of corn silage; W_N is the price of nitrogen; N is the units of nitrogen; W_I is the cost per unit of irrigation application; I is the units of irrigation applied; FC is the fixed cost; and f is the functional relationship between yield and nitrogen and irrigation water applied, with other factors of production held constant. To maximize profit, the first-order conditions (FOC) are

$$(3) \qquad \frac{\partial \Pi}{\partial N} = Pf_N - W_N = 0$$

$$(4) \qquad \frac{\partial \Pi}{\partial I} \; Pf_I - W_I = 0$$

where f_N and f_I are the partial derivatives of f with respect to N and I, respectively, and the second-order conditions (SOC) are

$$(5) \qquad \frac{\partial \Pi^2}{\partial N^2} = Pf_{NN} < 0$$

$$(6) \qquad \frac{\partial \Pi^2}{\partial I^2} = Pf_{II} < 0$$

where f_{NN} and f_{II} are the second derivatives of f with respect to N and I, respectively. The SOC mean that the marginal product of both N and I are decreasing at the profit maximizing level of application. From the FOC, the farmer has the incentive to apply nitrogen and irrigations until the VMP (Pf_N and Pf_I) equals the MFC (W_N and W_I), thus, yielding the optimal amounts of nitrogen and irrigation to apply. The farmer is assumed to ignore any environmental damage that these application rates may produce. The cost of environmental damage is not reflected in the farmer's cost function implied in equation (1) under this assumption.

The effects of a per unit tax on product output for correcting the external damage of nitrate leaching on nitrogen and irrigation application is examined mathematically. Since a per unit tax on output has the same effect on profit as a decrease in price, the FOC of the competitive question can be used to evaluate the incentive that the farmer has to reduce the rate of application of nitrogen fertilizers and irrigation water. Using the implicit function rule (Chiang), the following results are obtained,

$$(7) \qquad \frac{\partial N}{\partial P} = -\frac{f_N}{Pf_{NN}} > 0$$

$$(8) \qquad \frac{\partial I}{\partial P} = -\frac{f_I}{Pf_{II}} > 0 \ .$$

Since f_N, f_I, and P are greater than zero, and f_{NN} and f_{II} are less than zero, P being greater than $P - T$ (where T is the per unit tax), the farmer has the incentive to use less nitrogen and irrigation water.

The use of a per unit tax on nitrogen fertilizers to reduce nitrate leaching is evaluated using the FOC of the competitive question because a tax on fertilizer has the same effect as an increase in the price of fertilizer. The implicit function rule yields the following results,

$$(9) \qquad \frac{\partial N}{\partial W_N} = - \frac{-1}{Pf_{nn}} < 0$$

$$(10) \qquad \frac{\partial I}{\partial N} = - \frac{f_{NN} - f_{NI}}{f_{NI} - f_{II}}$$

since P is greater than zero and f_{NN} is negative. This implies that the farmer has the incentive to reduce the rate of nitrogen applied after a fertilizer tax is imposed. The impact of the fertilizer tax on irrigation application is unclear as can be seen below.

$$(11) \qquad \textit{If } f_{NI} \geq 0 \textit{ then } \frac{\partial I}{\partial N} > 0$$

$$(12) \qquad \textit{only if } f_{NI} < 0 \textit{ and } |f_{II}| > |f_{NI}| > |f_{NN}| \textit{ is } \frac{\partial I}{\partial N} < 0 \ .$$

Using the FOC and the implicit function rule, the sign of f_{NI} and magnitude determine whether the farmer has the incentive to apply more or less irrigation water. The sign of f_{NI} is not mathematically determinable. Its sign is, therefore, an empirical question. Based on experience it was assumed the $f_{NI} > 0$ for irrigated agriculture. If this is the case, then a nitrogen fertilizer tax gives the farmer the incentive to apply less irrigation water.

An emissions tax on each unit of nitrate emitted (leached) results in the following maximization problem for the farmer,

subject to:

$$(13) \quad Max\ \Pi = PY - W_N N - W_I I - TE - FC$$

$$(14) \quad Y = f(N, I)$$

$$(15) \quad E = g(N, I) \ \ for \ \ I > I^*$$

$$(16) \quad E = 0 \ \ for \ I \leq I^*$$

where T is the per unit emissions tax, E is the units of emission, g is the functional relationship between emissions and nitrogen and irrigation water applied, and I^* is the replenishment level of irrigation. Other terms are as defined previously. Empirical evidence indicates that g_N, g_I, and g_{NI} are positive (Pratt and Jury; Pratt; Randall; Smika et al.; Ludwick et al.; Timmons and Dylla). The case where $I = I^*$ is examined first. The maximization problem is as follows,

$$(17) \quad Max\ \Pi = Pf(N|I^*) - W_N - W_I I^* - FC$$

FOC

$$(18) \quad \frac{\partial \Pi}{\partial N|_{I^*}} = Pf_{N|I^*} - W_N = 0 \ .$$

The farmer has the incentive to apply nitrogen fertilizer up to where the VMP given I^* irrigation applications equals the MFC. The maximization problem when $I > I^*$ becomes,

$$(19) \quad Max\ \Pi = Pf(N, I) - W_N N - W_I I - Tg(N, I) - FC$$

FOC

$$(20)\quad \frac{\partial \Pi}{\partial N} = Pf_N - W_N - Tg_N = 0 \; ; \; Pf_N = W_N + Tg_N$$

$$(21)\quad \frac{\partial \Pi}{\partial I} = Pf_I - W_I - Tg_I = 0 \; ; \; Pf_N = W_I + Tg_I \; .$$

Since T, g_N, and g_I are positive, an emissions tax gives the farmer an incentive to apply less of both nitrogen fertilizer and irrigation water. Since drainage is required to maintain salt balance at almost all locations, this case is the most likely scenario. High monitoring costs of emissions for each field makes an emissions tax an unlikely policy instrument to control nitrate leaching.

The mathematical evaluation of a charge on ambient levels of a pollutant above a standard level has been done by Segerson and will not be repeated here. It is unlikely an ambient charge would be used as a control measure for nitrate leaching because the corrective measures for the free rider problem would greatly exceed the cost of the marginal damage caused by the leached nitrate.

BMPs restrict the production process to those inputs, technologies, and techniques that are deemed to be the "best" to use for reducing the environmental impacts of agricultural activities. They affect the production function itself, rather than acting directly through the supply function as output taxes do or through the cost function as input taxes, emission charges, and ambient fees do. The incentives that selected BMPs for control of nitrate leaching have on the "profit maximizing farmer" will be examined.

Limiting the amount of nitrogen that can be applied per acre has been suggested as a BMP. The maximization problem becomes,

$$(22) \qquad Max\ \Pi = PY - W_N N - W_I I - FC$$

subject to:

$$(23) \qquad Y = f(N, I)$$

$$(24) \qquad N \leq N^*$$

where N^* is the maximum amount of nitrogen that can be applied per acre. All other symbols are as defined initially. When the competitive solution level is equal to or less than N^*, there is no change in the amount of nitrogen or irrigation water applied as shown by the FOC equations (3) and (4). When the competitive solution level of nitrogen application exceeds N^*, the nitrogen constraint is binding, thus, limiting nitrogen application to N^*. The first-order conditions are reduced to a single equation (25),

$$(25) \qquad \frac{\partial \Pi}{\partial I\,|_{N^*}} = Pf_{I|N^*} - W_I = 0 \ .$$

Under the condition of (25) the farmer has the incentive to apply less irrigation water than under the competitive solution if nitrogen and irrigation water are complements. More irrigation water might be applied if the farmer perceived nitrogen fertilizer and irrigation water as substitutes. The possibility exists, with more irrigation water being applied, that more nitrate would be leached into the groundwater than the policy-makers had estimated.

Prescribing the type of nitrogen fertilizer that can be applied has been proposed as a BMP. It has been recommended that ammonium and urea-based fertilizer are less likely to leach than nitrate-based fertilizer. The maximization problem becomes (26),

$$(26) \qquad Max\ \Pi = Pf(N^{*},I) - W_{N^{*}}N^{*} - W_{I}I - FC = 0$$

FOC

$$(27) \qquad \frac{\partial \Pi}{\partial N^{*}} = Pf_{N^{*}} - W_{N^{*}} = 0$$

$$(28) \qquad \frac{\partial \Pi}{\partial I} = Pf_{I} - W_{I} = 0$$

where $N^{*}$is the prescribed form of nitrogen. The mathematics do not reveal the changes in nitrogen or irrigation applications. An evaluation must be done empirically, since both prices and marginal products relationships are not directly comparable between FOC (3) and (4) versus (27) and (28).

Split application of nitrogen fertilizer has also been suggested as a BMP. The production function is restricted to using those technologies that can apply nitrogen to growing crops. The maximization problem becomes (29),

$$(29) \qquad Max\ \Pi = PY - W_{N}^{s}N - W_{I}I - FC$$

subject to:

$$(30)\qquad Y = F(N,I)$$

FOC

$$(31)\qquad \frac{\partial \Pi}{\partial N} = PF_N - W_N^s = 0\ ;\ PF_N = W_N^s$$

$$(32)\qquad \frac{\partial \Pi}{\partial I} = PF_I - W_I = 0\ ;\ \ PF_I = W_I\ .$$

For the farmer to have an incentive to split the applications of nitrogen fertilizer under competitive situations, the VMP of splitting applications must be at least as great as the added MFC of splitting as compared to the VMP of a single application.

Limiting water application to estimate ET has been suggested as BMP for reducing nitrate leaching out of the root zone. The maximization problem is the same as was discussed in the emission tax section when irrigation was limited to the replenishment as shown in equations (17) and (18). Therefore, no further discussion will be given at this point.

The objectives of this study are to: (1) provide an economic analysis of selected BMP for irrigated silage corn grown in Box Elder County, Utah on three soils of varied water-holding and infiltration capacities, (2) determine the relative environmental impact of the selected BMP and measured by the amount of nitrate leached per acre, and (3) determine the effects of the type of commercial nitrogen fertilizer applied on the amount of nitrate leached and returns to management. An optimal economic application rate of nitrogen cannot be estimated using the recommendations of James and Topper because their implied nitrogen response function is linear. A high rate of nitrogen application was chosen. The rate selected was estimated to produce 1.7 times the county production average (UASS).

In chapter II, the effects of irrigation management are evaluated. Three soil types were selected to determine the effects of irrigation methods on returns to management and on environmental quality as measured by the amount of nitrate that leached out of the root zone by the following spring under two weather scenarios. One weather scenario was based on the 30-year average (1951-1980) precipitation level (USC). The other weather scenario was from April 1982 to March 1983 which had a precipitation level of 2.7 standard deviations above the mean.

In chapter III, nitrogen source and application methods are added to the evaluation. Three nitrogen sources were used in the study: (1) ammonium nitrate, (2) anhydrous ammonia, and (3) urea. Application methods for each fertilizer used included a single application, two applications (half in each), and an anhydrous ammonia added to irrigation water. Chapter IV presents a short summary of the study.

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CHAPTER II

NITRATE LEACHING AND IRRIGATION EVALUATED BY INTEGRATING A SOIL-CROP MODEL AND PRINCIPLES OF ECONOMIC ANALYSIS

Introduction

The eleven continental Western States have approximately 24 million acres of farmland under irrigation (USDA). This is the most productive farmland in the region, because water is less limiting as a factor of production. The amount of nitrogen needed to achieve the greater yields under irrigation is much greater than the amounts needed when water is a limiting factor of production.

Irrigated land generally must have some drainage to maintain salt balance. Drainage water can carry nitrate as well as other soluble salts below the root zone. "The amount of NO_3^- that leaches from a soil depends on the amount of water that moves through the soil and the amount of NO_3^- in the soil when water drains through and out of the soil profile" (Pratt, p. 320).

Other factors that affect the amount of nitrate leached and/or the concentration levels in groundwater include: (1) soil characteristics; (2) amount and timing of water applied as irrigation water or natural precipitation; (3) amount, timing, and species of nitrogen applied; (4) nature of the aquifer, i.e., recharge area and rate, depth, and rock formations (Edwards); (5) crop and plant population (IFIA).

Nitrates leached into groundwater may be associated with the following external costs: (1) methemoglobinemia (blue baby) in humans and other mammals;

(2) cardiovascular collapse and shock in horses; (3) possibility of cancer (USEPA); and (4) eutrophication of water bodies (IFIA) when nitrate-contaminated groundwater reaches surface water through wells or springs. Nitrate leaching is not only a possible source of external costs but also a private efficiency problem in irrigated agriculture as it represents the loss of an input before it is used in production.

The economic literature on externalities and/or nonpoint source pollution is both well-known and extensive (e.g., Dasgupta; Hanley; Kolstad; Legg, Fletcher, and Easter; Segerson; Stevens; Young and Crowder). Physical scientists throughout the world have developed an extensive body of literature on nitrate leaching (Devitt et al.; Duke, Smika, and Heermann; Hahne; Jokela and Randall; Kolaja, Vrba, and Zwirnmann; Ludwick, Reuss, and Langin; Muir et al.; Muir, Seim, and Olson; Onken, Matheson, and Nesmith; Pratt; Pratt and Jury; Ritter and Manger; Sheppard and Bates; Smika et al.; Timmons and Dylla; Tisdale, Nelson, and Beaton). The authors cited above and their references serve as the literature search for the interested reader.

> The growing public concern about agriculture and water quality has been accompanied by an increasingly negative view of agriculture . . . . Farmers are being admonished by people of substantial political influence to take responsibility for agricultural impacts on the environment. President Bush has endorsed a Federal initiative to protect groundwater resources from fertilizers and pesticides, stating explicitly that, ultimately, '. . . farmers must be responsible for changing production practices to avoid contaminating ground and surface waters' (Carriker and Purvis, p. 27).

Susan Offutt of the Office of Management and Budget has stated:

> . . . [The] fundamental issue here is the recognition and acknowledgement that, no matter what, agriculture disturbs the natural environment. The real issue is how much disturbance society will accept; not whether it will accept any at all.
>
> The bottom line is that farmers need to understand that there will indeed be a cost to pollution abatement and that it may well be their responsibility to accept those costs in moving quickly to meet society's objectives for protection of environmental quality (Carriker and Purvis, p. 27).

Although the work done by economists, soil scientists, and irrigation engineers is extensive, there are few bridges tying their work together. This paper is an attempt to integrate this knowledge to evaluate the economic incentives that the farmer has concerning irrigation management and how irrigation management affects nitrate movement below the root zone with the implication that it may at some point enter the groundwater supply. The purpose of this paper is to identify some of the costs associated with reducing the amount of nitrate that is leached out of the root zone by irrigation management on three soil types for the three weather scenarios under corn production, holding other factors constant.

Methodology and Simulation Procedures

Among the many water quality models, NTRM, A Soil-Crop Simulation Model for Nitrogen, Tillage, and Crop-Residue Management (Shaffer and Pierce), was chosen for modeling the physical properties of the soil and crop interactions. This model allows daily weather changes, simulation of tillage events, and identification of nitrogen location in the soil profile. It also allows simulation of the responses of various soil types. Three soils--a fine sandy loam, a silt loam, and a silty clay--were selected on the basis of water-holding capacity and other soil characteristics. The total soil profile was 66.14 inches deep for each soil simulated. Soil characteristics were obtained from soil survey data (Chadwick et al.).

Actual temperature and precipitation data for Corinne, Box Elder County, Utah for two years (1982-83 and 1985-86) starting on April 1st and ending on the 31st of March (USC) were used in the simulations. Average precipitation data for the thirty years (1951 to 1980) were also used with 1985-86 temperature data. The 1985-86 and 1982-83 precipitation levels were 131% and 160% of the 30-year average, respectively. All precipitation was treated as if it was rain in the simulations, although there are procedures as discussed by Crowder et al. for dealing with snowmelt. Modeling snowmelt is difficult because of the many factors (sudden temperature changes, frozen or thawed soil, snow movement by wind, etc.) that affect it. The results of the winter period are, therefore, more ambiguous than the results obtained during the growing season.

Corinne weather data was selected for the simulation for several reasons. It has a frost-growing season greater than 120 days. Corinne is on the lower Bear River, which is ranked sixth on Utah's priority watershed list (UBWPC). Last, the principal author has over 20 years experience farming there on soils similar to those used in the simulations.

Corn was selected as the crop for simulation because of its high nitrogen requirement which results in increased potential for nitrate leaching. Corn growth for silage (approximately 36,000 plants per acre) was simulated under constant management practices (except irrigation) for each soil type and weather condition. Management practices are typical for Box Elder County in Northern Utah (UASS 1989). Corn is usually planted in May and harvest starts in mid-September and may continue until late October. For the simulations, planting was assumed to occur on May 15th and harvest on October 1st. Two tillage events were simulated using NTRM. The first tillage event, on May 14th, was to incorporate the ammonium nitrate fertilizer applied into the top two inches of the soil. The second tillage event, on October 3rd, was plowing after harvest. Other cultural practices not modeled using NTRM include land planing (furrow irrigation is the standard method of irrigation for Bear River Canal Co. water users), chemical applications, rotary hoeing, cultivating, chopping, trucking, and packing silage in the pit silo.

Ammonium nitrate was applied in the top two inches at the rate of 200 pounds of elemental N per acre. Ammonium nitrate was chosen as the source of nitrogen because it is the most widely used nitrogen fertilizer in the area and half of the nitrogen applied would be in the nitrate form and, thus, available for early leaching. At the beginning of the season the residual nitrogen level was assumed to be 41 pounds per acre with 5.2 pounds per acre as nitrate. Residual nitrogen was assumed to be evenly distributed in the top 11.8 inches. There was no nitrogen below 11.8 inches in the initial condition for the simulations. With this nitrogen available, (241 lb./ac.) expected yield was 38 tons of silage per acre (James and Topper). This high target yield was chosen to evaluate the effects of high yield goals on the amount of nitrate leached below the root zone. This yield goal is higher than most farmers are likely to set, with a county average of 22.5 tons per acre (UASS).

Five irrigation regimes were chosen based on water rights of the Bear River Canal Company, which is the major supplier of irrigation water for Eastern Box Elder County. The water rights are approximately two inches per week per acre (BRCC). Depending on the cropping pattern, a farmer can irrigate every two weeks with six-, four-, or three-inch irrigations, or irrigate every week with three- or two-inch irrigations. The above levels were simulated. In addition, an estimated evapotransporation (ET) irrigation schedule was generated for those irrigation levels that resulted in nitrate leaching under the above scenarios, with the exception of the three-inch weekly irrigations on fine sandy loam and silt loam.

Furrow irrigation was used for each of the three soils simulated for six- and four-inch applications. Sprinklers are necessary for three- and two-inch applications on fine sandy loam and silt loam and two-inch applications on silty clay (Allen). It was assumed that the distribution of the irrigation water was uniform over the entire field. This is a departure from field conditions. Center pivots were assumed for the analysis of irrigation levels requiring sprinkler applications because they are capable of irrigating corn. Irrigations started on June 22 each year and ended by September 8 each year.

Irrigation water quality is high in the Bear River Canal system (James and Jurinak). Because of the low salinity, only a small drainage volume is required to maintain productivity. Irrigation water of lesser quality may require more drainage for the farmland to remain productive.

Costs of tillage events and other cultural and management practices were calculated using the crop budget generator, Cost and Returns Estimator (CARE), that was developed by the USDA Soil Conservation Service (SCS). Prices for new machinery and machinery useful life hours were estimated by Baugh. The yearly planned use for each machine was 10% of useful life hours. This allows the farmer to replace the machinery compliment every ten years. CARE calculates the machine cost of each field operation based on yearly planned machine hours, speed, width, estimated fuel consumption, fuel price, and field efficiency. Prices of other inputs were obtained from suppliers and farmers (BRVC, IFA, and UASS) and integrated into field operations through CARE. Operating capital was charged a 12% annual rate from the day of the field operation until October 31st. A land charge equal to the annual cash rental value for each soil type was included in the budget analysis.

Results

Soil attributes are important in determining the amount of water and nitrate that leach through the soil profile (Deer et al.). Soil texture (water-holding capacity) has been shown to be a major factor in explaining the amount of water and nitrate leached out of the root zone (Tindall et al.). The simulations demonstrated that, under the same weather and management, fine sandy loam leached the most, followed by silt loam, and silty clay. Table 1 shows the amount of water and nitrate that leached out of the soil profile for the 30-year average precipitation and six-inch irrigation simulations. Table 1 illustrates that the amount of water and nitrate leached is related to the water-holding capacity of the soil.

Fine sandy loam

The following discussion of the results will center on one soil and two weather scenarios, but other soils and water scenarios were evaluated. Fine sandy loam was selected as the soil because it is the most susceptible to leaching due to its low water-holding and high infiltration capacity. The 1985-86 weather simulations will not be discussed because they added nothing to the discussion of results which was not demonstrated by the 30-year average precipitation and the 1982-83 high precipitation simulations.

The contention that what is in the farmer's self-interest is harmful to the environment was examined by looking at the economic incentives of the farmer and the amount of nitrate leaching below the root zone. Table 2 summarizes the economic and environmental results for the two weather and the 15 irrigation scenarios.

Six-inch irrigations every two weeks under 30-year average precipitation is the control or reference treatment because it is the least labor-intensive of the furrow irrigations and is less capital-intensive than irrigation using center pivots. The move from six-inch irrigations to four-inch irrigations every two weeks results in a small increase in returns to management. Thus, the profit-maximizing farmer has the incentive to move to four-inch irrigations. The amount of nitrate that leaches out of the root zone is reduced to about 5% of the initial level. The move from six-inch to four-inch irrigations was an improvement for both the farmer and the environment.

The incentive of the same move under high precipitation is less clear because the returns to management are about equal, so there would be little incentive to change. The simulation of the change did result in a reduction of nitrate leached by about 40%. Thus, if the farmer expects precipitation to be near normal for any given year, the economic incentive is to move to four-inch irrigations every two weeks.

Utility-maximizing farmers may decide to apply more nitrogen fertilizer rather than increase their labor to the level needed to apply four inches of irrigation water every two weeks. An additional 40 pounds of nitrogen (the amount that the estimated added cost of labor to change to four-inch irrigations could purchase) applied as ammonium nitrate was simulated for six-inch irrigations every two weeks for the 30-year average precipitation and the high precipitation conditions. The results showed that the farmers have no economic incentive to apply more nitrogen because returns to management decreased and the amount of nitrate leached increased in both cases. The summary for these two cases was not included in Table 2.

The above must, however, be weighed against other goals. For example, farmers may be utility-maximizers rather than profit-maximizers. If this is the case, a utility-maximizer can reduce the number of six-inch irrigations to the number required to meet the ET needs of the crop. The ET need of corn in Corinne is about 25 inches. Four six-inch irrigations would supply 24 inches of water.

Simulations were run using six-inch irrigations spaced by estimated ET after the first irrigation at the starting date used in the other simulations. Four irrigations were used for the 30-year average precipitation simulation, and the result was returns to management decreased by about $10 per acre. Moreover, nitrate leaching was decreased by 92%.

Utility-maximizing for the high precipitation scenario yielded three six-inch irrigations. The results of the simulation indicate that the farmer could use three irrigations. This would reduce the returns to management by about $21 per acre, while nitrate leached decreased by 28%.

The farmer has no economic incentive to use three-inch irrigations. The cost of the center pivot and the cost of electricity make returns to management less than six- or four-inch irrigations using furrows. The returns to management are also less than those for applying two-inch irrigations every week using center pivots.

The marginal cost of reducing nitrate leaching can be calculated from the information in Table 2. The marginal cost of reducing nitrate leaching in the simulations from 70 pounds per acre to 3 pounds per acre was about -$0.06 per pound per acre under average precipitation. As a result, both the farmer and the environment were better off if the level of irrigation was reduced from six to four inches every two weeks. This could be done by shortening the length of the sets. The marginal cost of reducing the amount of nitrate leached from 70 pounds per acre using six-inch irrigations every two weeks to 5 pounds per acre by irrigating by estimated ET was about $0.15 per pound per acre. The marginal cost of eliminating the last three pounds of nitrate leached per acre was over $8 per pound. A technological change (center pivots) is required to keep the last three pounds from leaching. The above analysis demonstrates that fairly large improvements can be made in reducing nitrate leaching by irrigation management with little change in technology at relatively low cost. This analysis, however, assumes farmers can operate close to maximum yield. In field situations, soil spatial variability and irrigation application variability make this more difficult.

The analysis so far has assumed that irrigation water is uniformly distributed. Analysis can be made for different nonuniform irrigations by using relative weights of the simulation results. As an example, assume that 30% of a field receives six-inch irrigations, 40% receives four-inch irrigations, and 30% receives three-inch irrigations every two weeks. This results in an average of four inches, but the economic and environmental outcomes are not the same as the results obtained for the uniform simulation. Net returns to management are $255.74 per acre as compared with $268.96 per acre under the four-inch uniform simulation, while the amount of nitrate leached is 22.55 pounds per acre compared to 3.29 pounds per acre for the uniform application.

Improving the uniformity of application to 20% six-inch, 60% four-inch, and 20% three-inch irrigations every two weeks results in higher returns to management and less environmental impact. Returns to management increased by $4.41 per acre and nitrate leached was reduced by about six pounds per acre as compared to the less uniform system. Thus, uniformity of application of irrigation water has an important impact on both profitability and environmental quality. There is still the problem of soil spatial variability. Farmers have historically overirrigated to mask the "ugly" effects of visual spatial variability without regard to economic cost nor environmental impact. In the future, farmers may need to live with variability.

Figure 1 illustrates the movement over time of nitrate through the soil profile using four-inch irrigation every two weeks and the high precipitation scenario as an example. Data shown for June 19 was just before irrigating started. July 19 was after two four-inch irrigations. August 18 was after four four-inch irrigations. October 7 was after six four-inch irrigations and after the harvest. All of the nitrate in the soil profile is found below 30 inches by harvest time. Most of the nitrate that was in the soil profile on October 7 had leached below 68 inches by March 26. Thus, irrigation pushed the nitrate down in the soil profile where winter precipitation could push it out of the root zone. Only in those areas where winter precipitation is minimal is there likely to be much nitrate carryover on coarse-textured soils.

Silt loam

The profit-maximizing irrigation level on silt loam was six-inch irrigations by estimated ET (Table 3). In the simulations, this resulted in no nitrate being leached out of the root zone. Thus, the economic interest of the farmer is in harmony with environmental quality. Late-season irrigations seem to be a prime source of the nitrate leaching out of the root zone over the nongrowing season. This is illustrated by the simulations of the four-inch and two-inch irrigations by estimated ET where the last irrigation occurred later than the last irrigation of the six-inch irrigations by estimated ET. The nitrate leaching that occurred during the growing season was related to overirrigating at one time or too often.

Silty clay

The profit-maximizing production level was achieved in the simulations on silty clay using three-inch irrigations scheduled by estimated ET (Table 4). This resulted in no nitrate leaching in the simulations. Nitrate leaching out of the root zone only occurred when weekly three-inch irrigations were simulated. This study did not include the potential problems for this soil resulting from erosion or runoff due to low infiltration capacity.

Conclusions

The results of the analysis point to the following conclusions.

1. Soil characteristics are important in determining the amount of water and nitrate that leaches through the soil profile and should be considered important in determining the proper irrigation management techniques.
2. Each of the soils simulated had a different profit-maximizing irrigation schedule.
3. The profit-maximizing level of irrigation resulted in some nitrate being leached out of the root zone on the fine sandy loam simulated.
4. The amount of nitrate that leaches out of the root zone can be greatly reduced by irrigation management on sandy soils.

5. The profit-maximizing levels of irrigation water applied were near the estimated ET requirements in total amount of water applied, but the amount of water applied per application and the timing varied by soil type in the simulations.
6. The profit-maximizing level of irrigation per application for each soil type was little affected by the different weather scenarios.
7. The profit-maximizing level of irrigation on coarser soils pushed the residual nitrate down in the soil profile where it is more likely to be pushed out of the root zone, either by precipitation during the nongrowing season or by excess irrigation the next year before the plant roots can reach the nitrate.
8. The maintenance of water quality was not different from farmer goals in most cases. Only when the extreme position of no drainage were taken did farmer goals and environmental concerns diverge.

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Table 1. Water and Nitrate Leached Under Six-Inch Irrigation with 30-Year Average Precipitation, Corinne, Box Elder County, Utah

Soil Type	Inches of Water Held in Soil Profile at Field Capacity	Water Leached Out of Soil Profile in Inches	Nitrate Leached Out of Soil Profile in Pounds per Acre
Fine sandy loam	11.79	15.48	70.33
Silt loam	19.19	13.74	29.20
Silty clay	23.72	0.39	0

Table 2. Summary of Economic and Environmental Results of Weather and Irrigation Simulations on Fine Sandy Loam, Box Elder County, Utah

Weather Condition	Irrigation Level	Silage Yield (tons/acre)	Returns to Management ($/acre)	Water Leached (inches)	Nitrate Leached (lbs/acre)
30-year average precipitation (1951-1980)	Six inches every two weeks	37.17	265.23	15.48	70.33
	Four inches every two weeks	38.09	268.96	3.88	3.29
	Three inches every two weeks	36.25	203.98	2.28	0.44
	Three inches every week	35.70	161.74	12.15	69.08
	Two inches every week	37.79	217.84	1.19	0.00
	Six inches by estimated ET	36.31	255.37	5.60	5.34
	Four inches by estimated ET	36.91	254.10	3.28	2.23
Wet year April 1982 to March 1983 precipitation	Six inches every two weeks	33.52	206.27	23.76	117.51
	Four inches every two weeks	34.18	206.03	11.66	70.06
	Three inches every two weeks	32.09	136.33	7.48	35.93
	Three inches every week	27.22	21.85	22.85	167.36
	Two inches every week	33.59	150.08	11.21	66.59
	Six inches by estimated ET	31.81	184.60	10.18	33.38
	Four inches by estimated ET	35.67	234.18	8.31	32.23
	Two inches by estimated ET	34.70	196.11	4.85	16.38

Table 3. Summary of Economic and Environmental Results of Weather and Irrigation Simulations on Silt Loam, Box Elder County, Utah

Weather Condition	Irrigation Level	Silage Yield (tons/acre)	Returns to Management ($/acre)	Water Leached (inches)	Nitrate Leached (lbs/acre)
30-year average precipitation (1951-1980)	Six inches every two weeks	36.53	250.00	13.74	29.20
	Four inches every two weeks	36.90	244.95	2.31	0.00
	Three inches every two weeks	34.23	165.16	1.32	0.00
	Three inches every week	35.23	147.19	10.77	29.20
	Two inches every week	33.09	135.48	0.39	0.00
	Six inches by estimated ET	37.74	273.60	4.28	0.00
Wet year April 1982 to March 1983 precipitation	Six inches every two weeks	33.44	199.93	20.99	73.89
	Four inches every two weeks	34.61	208.09	8.90	17.63
	Three inches every two weeks	34.07	162.65	2.95	0.00
	Three inches every week	31.19	81.98	20.71	99.70
	Two inches every week	34.42	157.52	8.83	16.65
	Six inches by estimated ET	36.65	258.06	4.23	0.00
	Four inches by estimated ET	35.31	223.34	5.33	3.92
	Two inches by estimated ET	34.55	173.61	4.81	2.58

Table 4. Summary of Economic and Environmental Results of Weather and Irrigation Simulations on Silty Clay, Box Elder County, Utah

Weather Condition	Irrigation Level	Silage Yield (tons/acre)	Returns to Management ($/acre)	Water Leached (inches)	Nitrate Leached (lbs/acre)
30-year average precipitation (1951-1980)	Six inches every two weeks	31.78	197.55	0.24	0.00
	Four inches every two weeks	31.34	190.29	0.25	0.00
	Three inches every two weeks	27.77	130.71	0.24	0.00
	Three inches every week	36.41	259.57	7.83	4.27
	Two inches every week	30.01	112.32	1.00	0.00
	Three inches by estimated ET	38.35	299.18	1.42	0.00
Wet year April 1982 to March 1983 precipitation	Six inches every two weeks	27.36	123.85	2.74	0.00
	Four inches every two weeks	26.66	111.62	3.13	0.00
	Three inches every two weeks	24.33	73.07	3.49	0.00
	Three inches every week	34.66	232.16	15.22	28.31
	Two inches every week	32.42	155.48	7.53	0.00
	Three inches by estimated ET	34.51	237.58	4.65	0.00

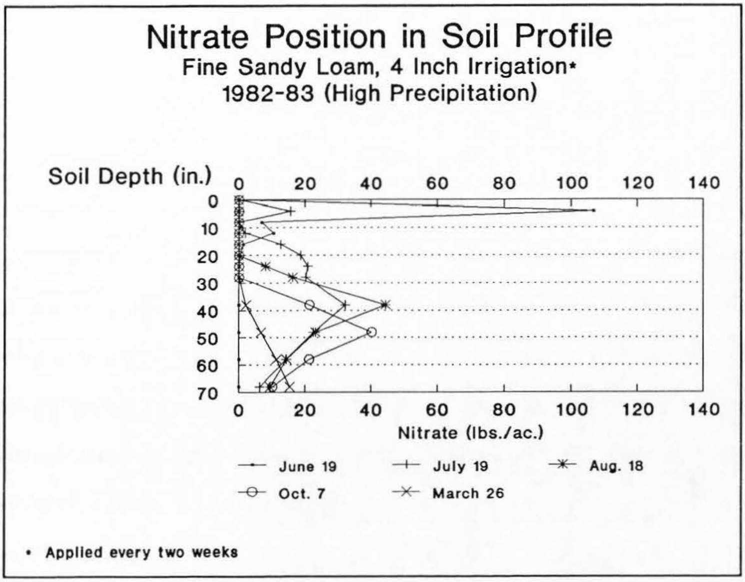

Figure 1. Nitrate position in soil profile on selected days for high precipitation with four-inch irrigations simulation on fine sandy loam.

CHAPTER III

AN ECONOMIC ANALYSIS OF THE EFFECTS OF NITROGEN SOURCE AND APPLICATION METHOD ON NITRATE LEACHING UNDER IRRIGATION IN THE ARID WEST

Introduction

Groundwater quality and fertilizer costs are important considerations for decision-makers involved in irrigated agriculture. The amount of fertilizer applied to irrigated crops has the potential to increase the level of nitrates in groundwater. The source of nitrogen, quantity and timing of application, and the quantity and timing of irrigations have been proposed as management variables to reduce the potential impact of irrigated agriculture on groundwater quality (Saliba; Newcomer). Although the work done by economists, soil scientists, and irrigation engineers is individually extensive in examining the effects fertilization practices have on groundwater quality and economic variables, there are few studies which tie their work together. This paper integrates this knowledge to evaluate the economic incentives that the farmer faces in selection of nitrogen source, application method, and irrigation management and how these choices affect nitrate movement below the root zone. The purpose of this paper is to identify selected costs which are associated with reducing the amount of nitrate that is leached out of the root zone. This analysis of corn silage production will account for different nitrogen and irrigation management options on three soil types for two weather scenarios, holding other factors constant.

Methodology and Simulation Procedures

Of the many water quality models, NTRM, A Soil-Crop Simulation Model for Nitrogen, Tillage, and Crop-Residue Management (Shaffer and Pierce), was chosen for modeling the physical properties of the soil and crop interactions. This model allows daily weather changes, simulation of tillage events, and identification of nitrogen location in the soil profile. It also allows simulation of the soil conditional crop responses of various soil types. Three soils (fine sandy loam, silt loam, silty clay) were selected on the basis of water-holding capacity and other soil characteristics. The total soil profile was 66.14 inches deep for each soil simulated. Soil characteristics were obtained from soil survey data for the eastern part of Box Elder County, Utah (Chadwick et al.).

Weather data for Corinne, Box Elder County, Utah were selected for the two weather patterns to be simulated. Average precipitation data for the 30 years (1951 to 1980) were used with the 1985-86 (near average) temperature data, starting on April 1st and ending on the 31st of March (USC), to simulate average precipitation conditions. High precipitation (1.6 times the 30-year average) conditions were simulated using actual temperature and precipitation data for April 1, 1982 to March 31, 1983. All precipitation was treated as if it was rain in the simulations, although there are procedures as discussed by Crowder et al. for dealing with snowmelt.

Modeling snowmelt is difficult because of the many factors (sudden temperature changes, frozen or thawed soil, snow movement by wind, etc.) that affect it. The results of the winter period are, therefore, more ambiguous than the results obtained during the growing season.

Corinne weather data were selected for the simulation for several reasons. It has a frost-free growing season greater than 120 days. Corinne is on the lower Bear River, which is ranked sixth on Utah's priority watershed list (UBWPC). Lastly, the principal author has over 20 years experience farming in Corinne on soils similar to those used in the simulations.

Corn was selected as the crop for simulation because of its high nitrogen requirement which results in increased potential for nitrate leaching. Corn growth for silage (approximately 36,000 plants per acre) was simulated under constant management practices (except irrigation, nitrogen source, and application method) for each soil type and weather condition. Management practices are typical for Box Elder County in Northern Utah (UASS 1989). Corn is usually planted in May and harvest starts in mid-September and may continue until late October. For the simulations, planting was on May 15th and harvest on October 1st. Two major tillage events were simulated using NTRM. The first tillage event, on May 14th, was to prepare the seedbed and, in some cases, incorporate the fertilizer applied into the top two inches of the soil. The second tillage event, on October 3rd, was plowing after harvest. NTRM does not simulate other cultural practices which include land planing (furrow irrigation is the standard method of water application for Bear River

Canal Co. water users), chemical applications, rotary hoeing, cultivating, chopping, trucking, and packing silage in the pit silo.

Nitrogen was applied at the rate of 200 pounds of elemental N per acre. Ammonium nitrate (NH_4NO_3), anhydrous ammonia (NH_3), and urea ($CO(NH_2)_2$) were chosen as the sources of nitrogen because they are the most widely used nitrogen fertilizers in the area. Single applications were applied on May 14th, the day before planting. Split applications of each fertilizer were made with 50% being applied on May 14th and 50% on June 29th. Fertigation was also simulated on fine sandy loam using anhydrous ammonia divided equally among all irrigations. At the beginning of the season the residual nitrogen level was assumed to be 41 lb./acre with 5.2 lb./acre as nitrate. It was further assumed that residual nitrogen was evenly distributed in the top 11.8 inches, with no nitrogen below 11.8 inches in the initial condition. This amount of available nitrogen (241 lb./acre) was expected to yield 38 tons of silage per acre (James and Topper). This target yield was chosen to evaluate the effects of high yield goals on the amount of nitrate leached below the root zone. This yield goal is substantially higher than most farmers are likely to obtain, given a county average of 22.5 tons per acre (UASS).

Irrigation regimes were chosen based on water rights of the Bear River Canal Company, which is the major supplier of irrigation water for Eastern Box Elder County. The water rights are approximately two inches per week per acre (BRCC). Depending on the cropping pattern, a farmer can irrigate every two weeks with six-, four-, or three-inch irrigations, or irrigate every week with three- or two-inch irrigations. Based on the water-holding and infiltration capacities of each soil type, irrigation levels were selected from the above levels for simulation. In addition, an estimated evapotransporation (ET) irrigation schedule was generated for those irrigation levels that resulted in nitrate leaching under the initial selected scenarios.

Furrow irrigation was used for each of the three soils simulated for six- and four-inch applications. Sprinklers are necessary for three- and two-inch applications on fine sandy loam and silt loam and two-inch applications on silty clay (Allen). Three-inch applications were not simulated on fine sandy loam or silt loam because preliminary work had shown them to be impractical and uneconomical. It was assumed that the distribution of the irrigation water was uniform over the entire field. This is a departure from field conditions. Center pivots were assumed for the analysis of irrigation levels requiring sprinkler applications because they are capable of irrigating corn. Irrigations started on June 22nd each year and ended by September 8th each year.

Irrigation water quality is high in the Bear River Canal system (James and Jurinak). Because of the low salinity, only a small drainage volume is required to maintain salt balance. Irrigation water of lesser quality may require more drainage to maintain salt balance for the farmland to remain productive.

Costs of tillage events and other cultural and management practices were calculated using the crop budget generator, Cost and Returns Estimator (CARE), that was developed by the USDA Soil Conservation Service (SCS). Prices for new machinery and machinery useful life hours were estimated by Baugh. The yearly planned use for each machine was 10% of useful life hours. This assumption "envisions" the farmer replacing the machinery compliment every ten years. CARE calculates the machine cost of each field operation based on yearly planned machine hours, speed, width, estimated fuel consumption, fuel price, and field efficiency. Prices of other inputs were obtained from suppliers and farmers (BRVC, IFA, and UASS) and integrated into field operations through CARE. Operating capital was charged a 12% annual rate from the day of the field operation until October 31st. A land charge equal to the annual cash rental value for each soil type was included in the budget analysis.

Results

Soil attributes are important in determining the amount of water and nitrate that leach through the soil profile (Deer et al.). Soil texture (water-holding capacity) has been shown to be a major factor in explaining the amount of water and nitrate leached out of the root zone (Tindall et al.). The simulations demonstrated that, under the same weather and management, fine sandy loam leached the most, followed by silt loam, and silty clay. This illustrates that the amount of water and nitrate leached (given any fertilizer application and irrigation regime) is related to the water-holding capacity of the soil (tables 5-10).

The following discussion of the results will center on one soil and the two weather scenarios, but most results may be generalized over the other soils types simulated. Fine sandy loam was selected as the soil because it is the most susceptible to leaching due to its low water-holding and high infiltration capacities.

Conventional wisdom, which holds that what is in the farmer's self-interest is harmful to the environment was examined by comparing the economic incentives of the farmer and the amount of nitrate leaching below the root zone. Tables 5 and 6 summarize the economic incentives and quantities of nitrate leached for fine sandy loam for the 30-year average precipitation and the 1982-83 high precipitation scenarios, respectively. The summaries for silt loam are in tables 7 and 8 and for silty clay in tables 9 and 10. Economic incentives are defined as changes in returns to management. A change in production practices that results in increased returns to management is taken as an incentive to the farmer to make the change. A change that reduces returns to management is viewed as a disincentive to change. An improvement in environmental quality is defined as a reduction in the amount of nitrate leached per acre. Concentration levels of nitrate in the water leached out of the root zone were not used as the measure of environmental quality because of the ambiguous relationship between amount of nitrate leached and concentration levels.

A single application of ammonium nitrate with six-inch irrigations every two weeks under 30-year average precipitation is the control or reference treatment because a single application of ammonium nitrate is the typical management practice in the study area and the six-inch irrigation scenario is the least labor-intensive of the furrow irrigations and is less capital-intensive than irrigation using center pivots.

The simulations indicate that farmers have the economic incentive to move away from single applications of ammonium nitrate to single applications of urea without regard to irrigation method or weather condition. Returns to management increase and the amount of nitrate leached out of the root zone is reduced. The differences in the amount of nitrate leached for the various nitrogen forms as shown in Tables 6 through 10 are dependent on temperature and soil moisture. The soil moisture of the top two inches in the simulations was low. This soil condition slowed the transformation of urea to ammonium and ammonium to nitrate (Tisdale et al.). If the soil moisture had been higher, the transformations to nitrate would have occurred sooner, increasing the likelihood that more nitrate would have leached below the root zone reducing the environmental benefits of changing nitrogen sources. Under the conditions of the simulation, what is in the best economic interest of the farmer is also a quality improvement for the environment. In response to the economic stimulus of higher returns, farmers in Box Elder County could be expected to increase their use of anhydrous ammonia and urea-based fertilizers.

Compared to single applications, split applications of nitrogen fertilizers significantly reduced the amount of nitrate leached out of the root zone only in the overirrigation simulations. This is another indicator that irrigation management is a key tool in managing nitrate leaching.

Split applications of anhydrous ammonia had returns to management at or near the maximum for most irrigation and weather conditions simulated. This is mostly due to the low cost of application. The cost of the applicator was included in the price of the anhydrous ammonia. Only the additional cost of the tractor to pull the applicator and the operator's labor were incurred by splitting the application into two parts. Whereas the farmer incurred the full cost of ownership and maintenance of the dry fertilizer applicator used to apply the second application of ammonium nitrate or urea.

Because all nitrogen fertilizers are transformed over time into nitrate, irrigation management is an important tool in reducing nitrate leaching. Farmers have the incentive to change irrigation practices to those that meet ET requirements. Overirrigation reduces both returns to management and environmental quality. The four highest returns to management simulations for the 30-year average precipitation runs for fine sandy loam were with irrigation levels near ET. There was little nitrate leaching in these simulations.

Similar results were found for the other soil types simulated. Under the high precipitation simulations, the three highest returns to management were irrigated at levels near ET with the exception of fertigation simulations which include six- and four-inch furrow applications. The latter exceptions are seldom used in practice and are not indicative of what would happen under field conditions.

There are several problems associated with fertigation using furrow irrigation. Nonuniform application and tail-water runoff are just two. Nonuniform water application was considered the major source of variability. The head of the field would be overfertilized because it absorbs the most water while the tail may be underfertilized. Soil variability of the field also contributes to the uniformity problem. In addition, runoff containing nitrogen may reduce environmental quality by entering rivers, streams, or other water bodies. These simulations were made to evaluate fertigation under the ideal condition of uniform application. Even under this assumption, fertigation with six-inch and four-inch irrigations were not economically competitive with the other application methods under average weather conditions. Only under conditions of extreme leaching were they competitive. Most of these problems can be overcome using well-managed sprinkler applications.

In this study, the returns to management was highest under fertigation with two-inch water applications (which require center pivots) for both weather conditions simulated. It would be interesting to extend this test to supplemental irrigations in more humid regions. Fertigation makes it feasible to feed nitrogen to plants as they need it, thus, reducing the amount of nitrate available to leach at any point in time (Newcomer). Fertigation also reduces the total amount of nitrogen applied to achieve comparable yields. Farmers who must use sprinkler application can use fertigation to improve profitability.

Irrigation management was an important determinant of nitrate leaching (tables 5 through 10). The economic incentives that irrigators have were analyzed for the three soils simulated along with the environmental outcomes. Four-inch irrigations on fine sandy loam were clearly dominant over six-inch irrigations. Four-inch irrigation had a mean return to management of $255.39 per acre and a standard deviation (SD) of $24.30 per acre, while six-inch irrigations had a mean return to management of $243.21 per acre with an SD of $34.44 per acre. This implies that a farmer can increase returns to management and reduce the variability of returns to management by changing from six-inch irrigations to four-inch irrigations. This change reduced the amount of nitrate leached per acre from a mean of 37.6 lb./acre to 18.3 lb./acre and reducing the SD from 32.6 lbs/acre to 20.2 lb./acre. Two-inch applications, which require center pivots for corn production, had a mean return to management of $195.72 per acre and an SD of $28.40 per acre. Changing from four-inch furrow applications to two-inch applications reduced mean returns to management by $53.63 per acre with a SD of $18.48 per acre. Under the assumption of perfect uniformity of application, there were only small differences in the amount of nitrate leached between four-inch and two-inch irrigations. Applications under field conditions would be less uniform for four-inch furrow irrigations than two-inch applications using center pivots. Thus, more nitrate leaching would be expected with four-inch furrow irrigations than the simulations produced. Nitrate leaching could be reduced by using center pivots to apply two-inch irrigations but at a mean cost to returns to management of more than $50 per acre.

The preference ordering of six-inch and four-inch irrigations on silt loam are less clear. Six-inch irrigations have a higher mean ($249.34 per acre) return to management than four-inch irrigations ($232.95 per acre); however, four-inch irrigations had a smaller SD ($20.24 compared to $23.91), implying less variability with four-inch irrigations than with six-inch irrigations. Nitrate leaching was significantly less with four-inch irrigations (mean 5.7 lb./acre; SD 6.49 lb./acre) than with six-inch irrigations (mean 35.9 lb./acre; SD 20.81 lb./acre). A change from four-inch furrow irrigations to two-inch center pivot irrigations would cost more than $85 per acre in mean returns to management, with an SD of $45.09 per acre. The change in the amount of nitrate leached would be closely related to the change in uniformity of application which was beyond the scope of this study, thus, no estimate will be made on changes in the amount of nitrate leaching that a change from four-inch furrow irrigations to two-inch center pivot irrigations would bring.

For silty clay, three-inch irrigations scheduled by estimated ET had the highest mean returns to management ($276.01 per acre; SD $26.02 per acre). No nitrate was leached in simulations using this irrigation scenario. Three-inch irrigations every week had the second highest mean returns to management ($253.40 per acre), however, there was some nitrate leaching (mean 12.9 lb./acre; SD 11 lb./acre) for simulations using this irrigation scenario. Thus, for silty clay, three-inch irrigations scheduled by estimated ET would be the preferred method of irrigation on the basis of returns to management and nitrate leaching.

Conclusions

The results of the analysis point to the following conclusions:

1. Soil characteristics are important in determining the amount of water and nitrate that leaches through the soil profile and should be considered important in determining the proper irrigation management techniques.

2. Each of the soils simulated had a different profit-maximizing irrigation schedule.
3. The profit-maximizing level of irrigation resulted in some nitrate being leached out of the root zone on the fine sandy loam simulated.
4. The amount of nitrate that leaches out of the root zone can be controlled by irrigation management.
5. The profit-maximizing levels of irrigation are near the estimated ET requirements in total amount of water applied, but the amount of water applied per application and the timing varied by soil type in the simulations.
6. The profit-maximizing level of irrigation per application for each soil type was little affected by the different weather scenarios.
7. The profit-maximizing level of irrigation on coarser soils pushed the residual nitrate down in the soil profile where it is more likely to be pushed out of the root zone, either by precipitation during the nongrowing season or by excess irrigation the next year before the plant roots can reach the nitrate.
8. Split applications of nitrogen did not reduce the amount of nitrate leached significantly except when overirrigation occurred.
9. Changing from ammonium nitrate to urea or anhydrous ammonia may increase returns to management and may reduce the amount of nitrate leached because of the time required for nitrification to occur.
10. Fertigation may increase returns to management for farmers who use center pivots, reduce nitrate leaching and the total amount of nitrogen applied.

11. The maintenance of water quality (low nitrate content) was not different from farmer goals in most cases. Only when the extreme position of no drainage was taken did farmer goals and environmental concerns differ.

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Table 5. Summary of Economic and Environmental Results Using 30-Year Average Precipitation Simulations on Fine Sandy Loam, Box Elder County, Utah

Irrigation Level	Fertilizer Application	Returns to Management	Water Leached	Nitrate Leached	Ave. Nitrate Concentration
		($/acre)	(inches)	(pounds/acre)	(ppm)
Six inches every two weeks	S[1] NH_4NO_3	265.24	15.48	70.68	20
	S NH_3	281.00	15.60	52.07	15
	S Urea	285.05	15.57	39.01	11
	X[2] NH_4NO_3	244.69	15.99	62.54	17
	X NH_3	289.32	15.57	35.79	10
	X Urea	281.89	15.65	29.79	8
	F[3] NH_3	243.14	16.44	20.30	5
Six inches by estimated ET	S NH_4NO_3	255.37	5.60	5.37	4
	S NH_3	287.49	5.58	4.47	4
	S Urea	287.50	5.58	3.04	2
	X NH_4NO_3	258.86	5.59	3.49	3
	X NH_3	289.77	5.58	3.94	3
	X Urea	280.45	5.58	2.68	2
	F NH_3	74.70	8.15	6.20	3
Four inches every two weeks	S NH_4NO_3	268.96	3.88	3.31	4
	S NH_3	282.55	4.00	2.33	3
	S Urea	297.64	4.04	2.06	2
	X NH_4NO_3	235.25	4.45	3.40	3
	X NH_3	297.77	3.95	1.97	2
	X Urea	262.21	5.27	3.76	3
	F NH_3	260.18	4.73	2.00	2
Four inches by estimated ET	S NH_4NO_3	254.10	3.28	2.24	3
	S NH_3	284.74	3.28	1.34	2
	S Urea	285.83	3.28	0.98	1
	X NH_4NO_3	258.11	3.28	1.52	2
	X NH_3	294.47	3.28	0.98	1
	X Urea	281.93	3.28	0.98	1
	F NH_3	214.11	4.39	1.60	2
Two inches every week	S NH_4NO_3	217.84	1.19	0.00	0
	S NH_3	224.17	2.80	0.81	1
	S Urea	228.18	2.81	0.00	0
	X NH_4NO_3	205.97	2.83	1.07	2
	X NH_3	226.29	2.80	0.54	1
	X Urea	196.86	3.07	0.00	0
	F NH_3	253.29	2.81	0.00	0

[1] Single application on May 14, one day before planting.

[2] Two applications of 100 lbs. of N, one on May 14 and one on June 29.

[3] Fertigated, the amount of NH_3 was divided equally between irrigations.

Table 6. Summary of Economic and Environmental Results Using 1982-83 High Precipitation Simulations on Fine Sandy Loam, Box Elder County, Utah

Irrigation Level	Fertilizer Application	Returns to Management	Water Leached	Nitrate Leached	Ave. Nitrate Concentration
		($/acre)	(inches)	(pounds/acre)	(ppm)
Six inches every two weeks	S[1] NH_4NO_3	206.27	23.76	118.11	22
	S NH_3	234.99	23.77	89.21	17
	S Urea	241.30	23.77	72.92	14
	X[2] NH_4NO_3	212.87	23.81	97.62	18
	X NH_3	239.45	23.78	77.40	14
	X Urea	233.48	23.79	70.06	13
	F[3] NH_3	254.54	23.93	31.60	6
Six inches by estimated ET	S NH_4NO_3	184.60	10.18	33.55	15
	S NH_3	205.22	10.17	23.17	10
	S Urea	210.82	10.17	13.69	6
	X NH_4NO_3	194.00	10.21	21.65	9
	X NH_3	209.67	10.17	15.75	7
	X Urea	202.89	10.19	10.56	5
	F NH_3	186.81	10.22	11.40	5
Four inches every two weeks	S NH_4NO_3	206.03	11.66	70.42	27
	S NH_3	236.28	11.71	50.28	19
	S Urea	239.39	11.71	42.77	16
	X NH_4NO_3	211.21	11.75	57.62	22
	X NH_3	241.62	11.71	42.59	16
	X Urea	244.44	11.73	40.35	15
	F NH_3	258.67	11.86	16.20	6
Four inches by estimated ET	S NH_4NO_3	234.18	8.31	32.39	17
	S NH_3	246.27	8.50	25.68	13
	S Urea	249.35	8.50	18.88	10
	X NH_4NO_3	228.75	8.57	28.90	15
	X NH_3	246.19	8.50	22.19	12
	X Urea	241.80	8.50	17.72	9
	F NH_3	247.55	8.96	10.00	5
Two inches every week	S NH_4NO_3	150.08	11.21	66.93	26
	S NH_3	166.40	11.24	57.08	24
	S Urea	168.89	11.25	49.57	19
	X NH_4NO_3	146.98	11.23	61.74	24
	X NH_3	167.27	11.23	53.77	21
	X Urea	160.47	11.26	50.02	20
	F NH_3	225.89	11.26	5.80	2
Two inches by estimated ET	S NH_4NO_3	196.11	4.85	16.46	15
	S NH_3	195.26	4.85	14.41	13
	S Urea	196.61	4.85	11.09	10
	X NH_4NO_3	177.80	4.85	15.75	14
	X NH_3	193.18	4.85	13.51	12
	X Urea	187.85	4.85	11.18	10
	F NH_3	224.70	4.85	0.80	1

[1] Single application on May 14, one day before planting.

[2] Two applications of 100 lbs. of N, one on May 14 and one on June 29.

[3] Fertigated, the amount of NH_3 was divided equally between irrigations.

Table 7. Summary of Economic and Environmental Results Using 30-Year Average Precipitation Simulations on Silt Loam, Box Elder County, Utah

Irrigation Level	Fertilizer Application	Returns to Management	Water Leached	Nitrate Leached	Ave. Nitrate Concentration
		($/acre)	(inches)	(pounds/acre)	(ppm)
Six inches every two weeks	S[1] NH_4NO_3	250.00	13.74	29.35	9
	S NH_3	268.37	13.44	22.37	7
	S Urea	280.06	13.45	12.26	4
	X[2] NH_4NO_3	238.28	13.49	22.64	7
	X NH_3	282.46	13.45	12.62	4
	X Urea	277.09	13.45	9.39	3
Six inches by estimated ET	S NH_4NO_3	273.60	4.28	0.00	0
	S NH_3	297.76	4.28	0.00	0
	S Urea	286.74	4.30	0.00	0
	X NH_4NO_3	256.23	4.31	0.00	0
	X NH_3	295.23	4.30	0.00	0
	X Urea	273.46	4.31	0.00	0
Four inches every two weeks	S NH_4NO_3	244.95	2.31	0.00	0
	S NH_3	268.92	2.31	0.00	0
	S Urea	256.45	2.30	0.00	0
	X NH_4NO_3	222.08	2.32	0.00	0
	X NH_3	266.54	2.30	0.00	0
	X Urea	245.48	2.31	0.00	0
Two inches every week	S NH_4NO_3	135.48	0.39	0.00	0
	S NH_3	109.80	1.78	0.00	0
	S Urea	92.32	1.81	0.00	0
	X NH_4NO_3	99.03	1.80	0.00	0
	X NH_3	105.12	1.81	0.00	0
	X Urea	103.89	1.81	0.00	0

[1] Single application on May 14, one day before planting.

[2] Two applications of 100 lbs. of N, one on May 14 and one on June 29.

[3] Fertigated, the amount of NH_3 was divided equally between irrigations.

Table 8. Summary of Economic and Environmental Results Using 1982-83 High Precipitation Simulations on Silt Loam, Box Elder County, Utah

Irrigation Level	Fertilizer Application	Returns to Management	Water Leached	Nitrate Leached	Ave. Nitrate Concentration
		($/acre)	(inches)	(pounds/acre)	(ppm)
Six inches every two weeks	S[1] NH_4NO_3	199.94	20.99	74.26	16
	S NH_3	223.93	21.01	61.20	13
	S Urea	241.89	21.02	39.64	8
	X[2] NH_4NO_3	202.02	21.08	63.53	13
	X NH_3	237.83	21.01	45.45	10
	X Urea	232.55	21.05	38.65	8
Six inches by estimated ET	S NH_4NO_3	258.06	4.43	0.00	0
	S NH_3	270.56	4.43	0.00	0
	S Urea	266.38	4.43	0.00	0
	X NH_4NO_3	242.40	4.43	0.00	0
	X NH_3	267.51	4.43	0.00	0
	X Urea	248.72	4.43	0.00	0
Four inches every two weeks	S NH_4NO_3	208.09	8.90	17.72	9
	S NH_3	240.91	8.91	13.87	7
	S Urea	244.84	8.93	6.26	3
	X NH_4NO_3	206.18	9.02	15.03	7
	X NH_3	252.81	8.94	9.04	4
	X Urea	237.15	9.00	6.53	3
Four inches by estimated ET	S NH_4NO_3	223.34	5.33	3.93	3
	S NH_3	228.19	5.34	3.31	3
	S Urea	219.52	5.31	1.79	1
	X NH_4NO_3	204.90	5.31	3.31	3
	X NH_3	213.67	5.31	2.86	2
	X Urea	208.99	5.30	1.61	1
Two inches every week	S NH_4NO_3	157.52	8.83	16.73	8
	S NH_3	165.26	8.84	15.84	8
	S Urea	165.16	8.84	9.31	5
	X NH_4NO_3	150.43	8.83	15.75	8
	X NH_3	157.37	8.84	13.42	7
	X Urea	155.95	8.83	10.47	5
Two inches by estimated ET	S NH_4NO_3	173.61	4.81	2.59	2
	S NH_3	181.26	4.81	2.24	2
	S Urea	181.56	4.81	1.16	1
	X NH_4NO_3	166.66	4.82	2.06	2
	X NH_3	173.32	4.81	1.70	2
	X Urea	172.51	4.80	1.07	1

[1] Single application on May 14, one day before planting.

[2] Two applications of 100 lbs. of N, one on May 14 and one on June 29.

Table 9. Summary of Economic and Environmental Results Using 30-Year Average Precipitation Simulations on Silty Clay, Box Elder County, Utah

Irrigation Level	Fertilizer Application	Returns to Management	Water Leached	Nitrate Leached	Ave. Nitrate Concentration
		($/acre)	(inches)	(pounds/acre)	(ppm)
Six inches every two weeks	S[1] NH_4NO_3	197.55	0.24	0.00	0
	S NH_3	190.54	0.24	0.00	0
	S Urea	194.02	0.24	0.00	0
	X[2] NH_4NO_3	183.74	0.24	0.00	0
	X NH_3	207.37	0.24	0.00	0
	X Urea	175.00	0.24	0.00	0
Four inches every two weeks	S NH_4NO_3	190.30	0.25	0.00	0
	S NH_3	212.91	0.25	0.00	0
	S Urea	195.58	0.25	0.00	0
	X NH_4NO_3	190.47	0.25	0.00	0
	X NH_3	206.84	0.25	0.00	0
	X Urea	201.85	0.25	0.00	0
Three inches every week	S NH_4NO_3	259.58	7.83	4.29	2
	S NH_3	265.58	7.83	4.03	2
	S Urea	267.86	7.83	0.00	0
	X NH_4NO_3	252.53	7.83	3.49	2
	X NH_3	273.93	7.83	2.68	2
	X Urea	272.74	7.83	0.00	0
Three inches by ET	S NH_4NO_3	299.17	1.42	0.00	0
	S NH_3	307.64	1.49	0.00	0
	S Urea	302.65	2.06	0.00	0
	X NH_4NO_3	296.51	1.64	0.00	0
	X NH_3	305.58	1.82	0.00	0
	X Urea	293.10	2.14	0.00	0
Two inches every week	S NH_4NO_3	112.32	1.00	0.00	0
	S NH_3	122.32	0.97	0.00	0
	S Urea	122.39	1.02	0.00	0
	X NH_4NO_3	105.93	1.00	0.00	0
	X NH_3	113.91	1.00	0.00	0
	X Urea	115.81	1.02	0.00	0

[1] Single application on May 14, one day before planting.

[2] Two applications of 100 lbs. of N, one on May 14 and one on June 29.

Table 10. Summary of Economic and Environmental Results Using 1982-83 High Precipitation Simulations on Silty Clay, Box Elder County, Utah

Irrigation Level	Fertilizer Application	Returns to Management	Water Leached	Nitrate Leached	Ave. Nitrate Concentration
		($/acre)	(inches)	(pounds/acre)	(ppm)
Six inches every two weeks	S[1] NH_4NO_3	123.85	2.74	0.00	0
	S NH_3	129.41	2.73	0.00	0
	S Urea	117.49	3.26	0.00	0
	X[2] NH_4NO_3	118.56	2.67	0.00	0
	X NH_3	117.88	3.07	0.00	0
	X Urea	109.58	3.29	0.00	0
Four inches every two weeks	S NH_4NO_3	111.62	3.13	0.00	0
	S NH_3	133.57	2.65	0.00	0
	S Urea	123.37	3.38	0.00	0
	X NH_4NO_3	103.97	2.83	0.00	0
	X NH_3	117.88	3.20	0.00	
	X Urea	107.07	3.36	0.00	0
Three inches every week	S NH_4NO_3	232.17	15.22	28.45	8
	S NH_3	239.77	15.23	27.29	8
	S Urea	245.77	15.22	18.07	5
	X NH_4NO_3	228.45	15.23	26.31	8
	X NH_3	251.79	15.24	23.62	7
	X Urea	250.66	15.22	16.91	5
Three inches by ET	S NH_4NO_3	237.58	4.65	0.00	0
	S NH_3	248.07	4.67	0.00	0
	S Urea	266.73	4.67	0.00	0
	X NH_4NO_3	240.95	4.65	0.00	0
	X NH_3	255.82	4.68	0.00	0
	X Urea	258.33	4.69	0.00	0
Two inches every week	S NH_4NO_3	155.48	7.53	0.00	0
	S NH_3	150.62	7.53	0.00	0
	S Urea	147.90	7.55	0.00	0
	X NH_4NO_3	139.52	7.53	0.00	0
	X NH_3	148.52	7.52	0.00	0
	X Urea	143.40	7.54	0.00	0

[1] Single application on May 14, one day before planting.

[2] Two applications of 100 lbs. of N, one on May 14 and one on June 29.

CHAPTER IV

SUMMARY

A soil-crop simulation model and principles of economic analysis were used to evaluate the economic and environmental impacts of common and possible irrigation and nitrogen management practices for growing corn in Eastern Box Elder County, Utah. The results of the study indicate that irrigation management is important for both the economic well-being of farmers and water quality. It was shown that irrigations that supply water to meet the ET needs of the crop without overapplication of water result in the highest returns to management with only small amounts of nitrogen being leached out of the root zone. Irrigation management was shown to be more important for controlling nitrate leaching than nitrogen source or application method. Nitrogen source and application method became important in reducing nitrate leaching only when water applications were greater than the ET needs of the crop. Farmer goals of high returns and keeping nitrogen in the root zone were shown to be complementary with water quality concerns except in the extreme case where no drainage would be permitted. If no drainage were permitted, irrigated farmland would become unproductive over time as salts accumulated in the root zone of the soil profile. Efforts to inform farmers of the benefits of efficient irrigation and nitrogen applications have the possibility of improving farm income and water quality.

VITA

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Doctor of Philosophy

Dissertation: A Simulation of the Economic Effects of Alternative Soil Types and Nitrogen Sources on Nitrate Leaching on Irrigated Agriculture in Utah

Major Field: Economics

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