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STRATEGIES FOR REDUCING GROUNDWATER POLLUTION FOR AGRICULTURE: THE CASE OF IRRIGATED PRODUCTION IN OREGON

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STRATEGIES FOR REDUCING GROUNDWATER POLLUTION FOR AGRICULTURE: THE CASE OF IRRIGATED PRODUCTION IN OREGON

Technological advances in agricultural production over the past 40 years have contributed to the high standard of living enjoyed by many in the United States. Extensive use of chemicals (such as pesticides and inorganic fertilizers) to enhance yield and improve crop quality has played a major role in creating this highly productive U.S. agricultural system. Although the adoption of chemicals has kept food cost relatively low, there have been substantial environmental costs associated with the heavy dependence on some of these inputs. One environmental concern receiving increased attention is pollution of groundwater by agricultural chemicals. Although agriculture is not the only source of groundwater pollution in the U.S., it potentially represents the most serious long-term problem because 1) pollution cannot be readily traced to particular individuals or locations, and 2) the area vulnerable to pollution is extensive [CAST].

The implications of groundwater pollution are significant. About 50 million people rely on groundwater from areas identified by the USDA as vulnerable to agriculture-related groundwater pollution [Lee and Nielsen]. Furthermore, about 19 million people obtain their water from private wells, which are more vulnerable to pollution than municipal wells. In addition, the potential for surface water pollution from groundwater is also an important environmental concern; approximately 30 percent of surface water streamflow is from groundwater sources [Saliba].

Perhaps the single most common agricultural chemical pollutant is nitrogen, in the form of nitrates which are water-soluble. Leaching of nitrogen fertilizers is the primary source of nitrate contamination of groundwater. High nitrate levels can be attributed to the low relative cost of nitrogen and other chemical fertilizers, the ease with which nitrates move in soil, and the desire by many farmers to maximize yields. The human health consequences of nitrate exposure are potentially severe, including methemoglobinemia (blue-baby disease) in infants and gastric cancer in adults [Bower]. Groundwater pollution can also contribute to surface water contamination.

Irrigated farmland, in particular, has significant potential for nitrate groundwater pollution. Irrigation allows a farmer to control the soil moisture level in the root zone, thereby ensuring that the crop is not water-stressed. Attempts to keep soil moisture at a near optimum level for physical output, however, often results in excessive water applications and the resulting leaching of water (and nitrates) below the root zone.

Public concern over the health consequences of pollution are motivating US EPA and state environmental agencies to expand their regulatory activities on non-point pollution. As regulations are promulgated to achieve such reductions, it is important that policymakers also know what costs will be imposed on agriculture and its constituents to meet lower pollution standards. Reduction of nitrate leaching requires modification of farmers' management practices which, in turn, may lead to reduced profits. Regulations which require major reductions in nitrate groundwater pollution may also result in significant shifts in crop production between regions of the U.S., thereby increasing food costs for consumers. On the other hand, elimination of nitrate pollution may be possible with relatively little effect on the farm economy, if mitigative alternatives are available. Which situation applies is thus an important research issue.

Objectives

The research presented here is part of an ongoing research effort at Oregon State University to assess the farm-level effects of nitrate pollution reductions. Specifically, the analysis identifies possible changes in farm management strategies and farm income resulting from reductions in nitrate pollution levels. The empirical focus is on the Columbia Basin of North Central Oregon, an important agricultural area in the Pacific Northwest.

Assessment of the economic effects of nitrate pollution reductions requires an understanding of the linkages between management practices and groundwater pollution at the farm level. This analysis attempts to capture these relationships using economic, agronomic and hydrologic models. Linkages between these models permit measurement of the producer-level costs of reducing the quantity of nitrates leached into the groundwater in the study area. The results also suggest what changes in management practices may be necessary to minimize production costs should restrictions on leaching of nitrate and (or) irrigation water be imposed.

The study area is located in Umatilla and Morrow Counties in the Columbia Basin of central Oregon. This area contains about 244,000 acres of irrigated land, of which 137,000 is irrigated using center pivot systems [Miles]. There are 208,000 acres of sandy soils in the study area [Johnson and Makinson; and Hosler]. The principal crops in this area are alfalfa, potatoes, winter wheat, and field corn. In terms of climate and soils, this area is somewhat similar to other regions of the Columbia Basin, although with less diversity in irrigation systems.

Much of the Columbia Basin has experienced an increase in the concentration of nitrates in the groundwater. In the study area, for example, the Oregon

Department of Environmental Quality found that nitrate levels in 11 of 25 wells tested exceeded current US EPA standards (10 mg N/l). In fact, some nitrate concentrations were found to be as high as 80 mg N/l [Pettit].

Methodology

The methodology includes the development and linking of two different types of models. The first is a crop simulator from the CERES family of plant simulation models, which accounts for water and fertilizer use by a crop, amounts of water and fertilizer leached throughout the season, and resulting yield [Ritchie, Godwin and Otter-Nacke; Ritchie, Mogusson, Hodges; and Jones and Kiniry]. CERES models for potatoes, corn and wheat have been adapted for use in the study area. These crops form the basis for the present paper.

In simple terms, the CERES models estimate daily potential photosynthesis based on weather, accumulated biomass, leaf area, and genetics; CERES then uses water and (or) nitrogen stress estimates to calculate actual photosynthesis. The distribution of resulting carbohydrates depends on the stage of plant development. The timing of the development stages, including the harvest date, are determined endogenously, based solely on thermal time except for emergence and termination dates for potatoes which are determined exodengenously. Furthermore, root depth is determined endogenously based on daily carbohydrate production.

Treatment of water and nitrogen balances in CERES are somewhat asymmetric. Insufficient quantities of water and (or) nitrogen will inhibit growth of the plant, thereby reducing final yield. But excess quantities of water and nitrogen generally do not inhibit yields[1]. Most of CERES's stress calculations are based

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[1] An exception is potatoes, where excessive nitrogen concentration will decrease yields due excess leaf biomass.

on what is commonly called 'The Law of the Minimum'. The Law can be expressed as:

$$B = \mathrm{Min}\ (f(Sa), f(N), M)$$

where B is biomass from a single days growth, f(Sa) is the maximum biomass as imposed by soil moisture levels, f(N) is the maximum biomass under a given soil nitrogen level, and M is the maximum biomass imposed by other factors such as weather and genetics [Waggoner and Norvell; and Lanzer, Paris, and Williams]. In economic terms, a von Liebig production function is assumed such that the rate of technical substitution is zero between soil moisture, soil nitrogen, and other factors (moisture and nitrogen levels are technically independent until one becomes limiting in which case they are complements).

The second model is a dynamic optimization model for scheduling irrigation and fertigation decisions. It uses a foreword recursive dynamic programming like algorithm. The formulation is largely that of an open-loop stochastic control model [Zavaleta, Lacewell, and Taylor]. The optimization model determines daily water and nitrogen applications so as to maximize per acre returns above variable costs, subject to any restrictions imposed on the system. The optimization model utilizes the CERES crop simulator output to identify changes in yields and hence returns from different irrigation and fertilization strategies. The model evaluates those returns versus the cost of water and fertilizer applications for each strategy, as well as the net returns of competing irrigation and fertilization strategies.

Application

Within the optimization model, the producer is maximizing a before tax net return function for a given hectare with respect to the two decision variables (irrigation and fertilizer quantities), two state variables (soil moisture and nitrogen), exogenous random factors, and input and output prices. The marginal return function is defined by the marginal yield function (or the incremental change in yields) when moving between stages, the output price, variable harvest cost, water and fertilizer costs[2], and irrigation and fertilizer labor costs[3]. Fixed costs associated with a given crop, such as land, capital, and planting costs are irrelevant in the decision-making algorithm because they are viewed as sunk costs. Variable costs associated with irrigation and fertilization activities are the only expenditures which affect the decision set. The model used typical price and cost levels in the study area for the fall of 1983. The optimization model has constraints to restrict irrigation and fertilization decisions to be either zero or above some minimum amount[4] and also restricts the irrigation and fertilization amounts to be less than or equal to specified levels.

An important objective of this assessment is to portray the irrigation and fertilization decisions as they are viewed from the farmer's perspective as much as is possible. On the surface, it appears that farmers on irrigated land could eliminate the majority of nitrate leachate by more careful management of nitrogen and water applications. Specifically, uncertainty in the decision making

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[2] Variable costs include energy costs associated with pumping and input costs.

[3] Labor costs include such items as labor to turn on and off the pumps and labor to connect the fertilizer tanks.

[4] This integer type constraint (of requiring a minimum amount of irrigation if irrigation quantity is greater than zero) is based on physical limits on the equipment (e.g. maximum speed of the circles) and the fact that farmers will not make applications of water or nitrogen less than some minimum level. Inclusion of such a constraint is not practical with optimal control formulation without using computationally intensive routines such as Bender's decomposition [Perry, McCarl, and Gray], which emphasizes the necessity for the use of discrete optimization technique when solving this problem.

process, periods of high evapotranspiration, and heterogeneity in the physical environment all contribute to the occurrence of significant levels of nitrate pollution on irrigated lands.

Leaching will not occur unless moisture levels in the soil exceed field capacity. Imperfect knowledge about deficiencies in soil moisture levels in the crop root zone at the time of the irrigation decision may result in an excessive application of water, particularly under risk aversion. Similarly, imperfect knowledge about fertility levels may also result in excess nitrogen applications, resulting in potentially greater nitrate pollution. In formulating the optimization model, however, it is assumed that the farmer knows with certainty the current state of her or his fields.[5]

Even when perfect knowledge exists about current nitrogen and moisture levels, uncertainty about future events may cause unintentional leaching. For example, a heavy rain immediately after irrigation can cause extensive leaching. Actual efficiency of sprinkler systems for a particular irrigation set may be greater than expected, resulting in more water entering the soil than anticipated. Reduction of nitrate leaching therefore requires some modification of a farmer's management practices. Heterogeneity in the physical environment can also cause serious leaching problems. A field that is relatively homogeneous in soil type may have substantial variability in water holding capacity. Thus, a farmer who irrigates to ensure that the most drought-prone part of a field is never stressed will inevitably over-water the rest of that field. Further, since most irrigation systems do not apply a uniform amount of water across a

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[5] This is a strong assumption for fields in grain crops. However, intensive level of management used to produce potatoes in the region suggests such information is generally available.

field, the temptation is to apply more water than is required for most of the field.

To address some of these issues, several special features were built into DP-CERES. Irrigation and fertilizer decisions are made each day based on expected, rather than actual, weather throughout the remainder of the growing season, but final outcomes of those practices use a real weather year. The use of expected weather is necessary because CERES needs weather for the entire growing season to compute yields from a given irrigation pattern. Irrigation efficiency is treated as a normally distributed random variable with the optimization model using the mean for its decisions. To simulate the soil heterogeneity that could exist in a given field, routines were added to allow for sub-fields with distinct soils and yields but receiving the same management strategies. Decisions are based on the weighted average of the sub-fields.

Application of an optimizing technique to real world fertilizer and irrigation data can suggest the extent to which producers may or may not be over applying nitrogen or water. The following analyses are based on actual producer's practices within the study area. Specifically, actual field data on fertilizer rates and frequencies, irrigation schedules, yields, and soil nitrate levels are used to establish base model conditions for each crop.

Results

The focus of these analyses is to investigate the changes in yields, profits and nitrate leachate for three crops (potatoes, winter wheat, and field corn) under four fertilizer-water application situations. The four scenarios reported include 1) a base case that replicates the effect of current irrigation and fertilization practices; 2) an analysis reflecting an arbitrary 25 percent reduction in base-case applied nitrogen; 3) an optimal solution based on the DP-

CERES models; and 4) a 25 percent reduction in applied nitrogen for the optimal case. All solutions were generated under 1988 weather conditions for Umatilla County (Oregon) and expected weather as generated by WGEN [Richardson, and Wright].

The results of these four simulations are presented in Table 1. The table contains information on nitrogen and water applications, yields, nitrate leachate and profits under each scenario for each crop. The base case, representing actual producer behavior (as reported by producers in the area), provides a benchmark against which the effects of alternative nitrogen and water application strategies can be evaluated. Because of limitations on farm level data, the base corn and wheat model used a silty instead of sandy soil. Therefore, the optimization models for corn and wheat were first run using a silty soil, then run with a high-risk sandy soil to show the effect of water holding capacity on leaching rates. The results of the base models for corn, wheat, and potatoes indicate leachate levels of approximately 2.4, 1.5, and 5.1 kg/ha nitrates, respectively.

The first point of comparison is between the base case and the optimal solution of the DP-CERES model for each crop. As is evident from the table, movement to optimal timing of nitrogen and water applications generally resulted in less total water and nitrogen applied, substantially less total nitrogen leachate, a slight increase in yields, but greater profits for all three crops. Thus, if the routines predicted by the optimization model were followed under the 1988 crop year conditions, producers could in some cases reduce water and/or nitrogen applications, increase profits, and reduce nitrates leaving the root zone. The above results for the optimization model are "best case" estimates for a given weather year. Alternative real weather years may not yield the same outcome.

As discussed above, additional optimization models were run for corn and wheat using high-risk sandy soils. The results indicate that yields and profits decrease significantly and water usage and nitrate leachate increase significantly. The reason for these results is simply that it is less costly to minimize water stress and percolation on soils with moderate water holding capacity than on soils with low water holding capacity.

As a further point of comparison with optimization models which assume sandy soils, we also investigated the effects of an arbitrary 25 percent reduction of nitrogen on both solutions. This involved using the same nitrogen application schedule as the optimization models but reducing each application by 25 percent. This case thus corresponds to a situation where producers are forced or choose to reduce application levels by a fixed percent, but followed the same schedule recommend by the optimization model. The results for corn suggest that such a reduction decreased nitrogen leachate by approximately 4 percent from the optimization model. Yields were reduced about 14 percent, resulting in a profit loss of approximately $209. For wheat, a 25 percent reduction of nitrogen increased leachate by about nine percent[6]. Yields were reduced about ten percent, resulting in a profit loss of approximately $125. For potatoes, a 25 percent reduction of nitrogen reduces leachate by about two percent. Yields were reduced about 22 percent, resulting in a profit loss of approximately $962. As expected, imposing this fertility constraint on nitrogen

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[6] This counter intuitive sign for the change in leachate rates occurred because the early season nitrogen stress limited the ability of the plant to use nitrogen latter in the season. Thus, increasing the opportunities for mineralized nitrogen to leach.

applications under efficient timing of nitrogen and water applications imposed large costs on farmers, with little change in nitrate leachate.

Conclusions

The benefits of maintaining clean groundwater are substantial and obvious. For some areas, a change in current farming practices is necessary to maintain or achieve a reduction in groundwater nitrate levels. These changes will, however, likely result in increased costs for farmers and (or) lower crop yields. The results of the analyses reported here suggest that some nitrogen application reductions can be accomplished with little or no loss in profits, especially on fields with moderate to large water holding capacities. By changing the timing and application rates of nitrogen and water, profits for corn and wheat may be increased while reducing total nitrogen application levels. However, once these efficiencies are obtained, further reductions in nitrate leachate can only be achieved at substantial costs to producers.

Note that these results are for only three crops. Further, these results are based on specific fields of well managed, highly capitalized farms. They may not reflect management decisions or field conditions of other producers. If producers are already closely managing their water and fertilizer applications, potential leachate reductions may not be achievable without profit penalties. Also, no data were available for empirical validation of leachate estimates at the time of this analysis. The optimization model is not assured global properties because the state variables do not fully describe the state of the system at any stage in the solution and because the marginal yield calculations must be inferred indirectly from final yields. Furthermore, given the ex post nature of algorithms based on dynamic programming, this technique cannot be used for real time irrigation and fertigation scheduling. Finally, optimizing crop mixes for the whole farm may allow further total nitrogen reductions without profit penalties.

Table 1. Nitrogen, Water, Yield, and Profit Levels, by Crop.

Type of Analysis	Pred. Yield kg/ha	Profit $	Quant. Water Appl. mm	Quant. Nitr. Appl. kg/ha	Quant. Water Leach mm	Quant. NO_3 Leach kg/ha	Change in Profits $/ha
Wheat:							
Current Practices	8,779	1,207	605	298	66	1.53	-
Base Model w/Shano Silt	9,176	1,280	394	303	11	0.92	73
Base Model w/Quincy Sand	9,102	1,253	531	280	45	3.17	46
Base Model w/25% Fixed N Reduction	8,156	1,128	531	210	50	3.44	-79
Field Corn:							
Current Practices	11,424	1,010	720	320	42	2.37	-
Base Model w/Shano Silt	12,019	1,100	456	383	0	0.00	90
Base Model w/Quincy Sand	11,992	1,067	605	391	24	2.07	57
Base Model w/25% Fixed N Reduction	10,342	858	605	293	25	1.98	-152
Potatoes:							
Current Practices	58,986	4,081	711	434	18	5.11	-
Base Model w/Quincy Sand	61,007	4,224	799	400	14	2.30	143
Base Model w/25% Fixed N Reduction	47,504	3,262	799	300	14	2.25	-819

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