The Role of Soil Test Information in Reducing Groundwater Pollution

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Abstract:

Will nitrogen soil testing improve groundwater quality enough to decrease the demand for direct regulation? This question is addressed using a dynamic simulation model of irrigated agriculture in eastern Oregon. Results indicate that soil testing reduces applied nitrogen, increases farm profits and improves groundwater quality, but not enough to avoid regulation.

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Soil tests provide information concerning the amount of nitrogen and other macro and micro nutrients in soil available for crop consumption. This information is valuable to producers who want to eliminating excess fertilizer and reduce crop production costs. An external consequence of eliminating excess fertilizer is reduced leaching of nutrients and improved groundwater quality. In agricultural regions where groundwater quality problems have been identified, producers may be able to avoid environmental regulation by taking advantage of information that reduces leaching of nutrients and improves groundwater quality.

Past studies have shown that soil test information can be valuable to producers. However, these studies tend to focus on cost savings and only mention the potential for improved groundwater quality (Adams et. al., 1983; Babcock and Blackmer, 1992; Babcock et. al., 1996; Fuglie and Bosch, 1995; Musser et. al., 1995; Wu et. al., 1996). These studies indicate that soil testing can reduce nitrogen fertilizer applications 15 to 41 percent while increasing per acre return 20 to 50 dollars, depending upon location and crop.

Musser et. al. acknowledge that the effect of a soil test on excess nitrogen is only an indicator of environmental performance. To measure actual environmental performance requires linking farm level input decisions with ambient levels of an environmental contaminant. Because of the difficulty involved in linking nitrogen input decisions to groundwater nitrate concentration, no previous study has quantified changes in groundwater quality as a result of utilizing soil tests. While Babcock and Blackmer make no effort to measure the value of changes in nitrate contamination of groundwater, they do pose the following question which is the crux of this present investigation. Specifically, is it possible that voluntary adoption of soil testing will lower nitrogen applications sufficiently to decrease the demand for direct regulation?

The purpose of this paper is to assess the impact of soil testing on ambient groundwater quality as well as producer profit. The empirical focus is an irrigated agricultural region in eastern Oregon. Soil testing is assessed using a spatially distributed, dynamic simulation model which links economic behavior with the physical processes that determine groundwater quality.

The Study Region, Groundwater Concerns and the Use of Soil Tests

The empirical focus of the study is an irrigated agricultural region in east, central Oregon. The study region is high desert; annual precipitation ranges from 5 to 16 inches, with an average of 10 inches. Irrigation is required for crop production and surface (flood) irrigation is the principal method of application. The study region encompasses 32 square miles (in Malheur county), of which 17,860 acres (28) square miles is farmed.

Many crops (including fruit, vegetable and seed crops) are grown here. However, in this investigation, we focus on the five major crops in terms of acreage; soft white spring wheat, onions, potatoes, sugar beets and hay (a composite of meadow hay and alfalfa). These five crops represent approximately 72 percent of the crop acreage in the county and 54 percent of total crop sales in 1992 (MCES, 1992). Onions, potatoes and sugar beets have a large impact on the county economy in terms of jobs created by processing, handling and field labor. Onions are the most valuable cash crop in the study area (6 percent of the acreage and 25 percent of crop sales in 1992).

Between August of 1988 and April of 1990, 199 wells in the shallow aquifers were sampled. In this sampling, 32 percent of the wells were found to have nitrate levels which exceed the federal standard of 10 parts per million (ppm or mg/l) for municipal water supplies. Because of the groundwater quality problems identified here, the area was designated by the Oregon State Department of Environmental Quality (ODEQ) as a Groundwater Management Area (GMA).

As a result, a groundwater management committee was formed and several years of extensive data collection and analyses of the geo-hydrology of the region followed. This data was used to develop an action plan to improve groundwater quality. The action plan relies on voluntary approaches, but if these are not successful then (unstated) mandatory actions will be considered. Specifically, a regulatory approach will be considered if there is not evidence that nitrate levels will reach 7 ppm by July 1, 2000.

Producers in the study region who test their soils generally contract this work out to private companies who specialize in soil sampling and testing. Soil tests cost $15 per sample for nitrogen and $35 per sample for a complete nutrient profile which includes nitrogen, phosphorous, potassium, soil organic material and miner nutrients. One sample is taken per field where a sample consists of numerous probes taken at random throughout the field. The soil probes generally extract a core 1 foot in depth. An exception is sugar beets where the first and second foot of soil is tested (the producer is charged for two soil tests).

Soil testing is identified in the Groundwater Management Action Plan as a method for reducing groundwater nitrate concentration. Hence, there has been great effort on the part of the local Extension Service to educate producers and to encourage them to test their soils for nitrogen before applying fertilizer. Currently, 100% of the potato and sugar beet fields in the study region are soil tested. Wheat and onion fields are also soil tested, but at a much lower rate. Specifically, up to 10% of the wheat fields and 80% of the onion fields are soil tested. Further improvement in groundwater quality is possible if all fields were to be soil tested. In the analysis that follows, we assess whether voluntary adoption of soil testing on all fields is profitable to producers and if groundwater quality is improved.

A Simulation Model of Soil Testing

The affect that soil test information has on producer profit and groundwater quality is measured utilizing a spatially distributed, dynamic simulation model linking the economic and physical processes which determine groundwater quality. The integrated model is a composite of three sub-models (economic, soil water solute transport and groundwater solute transport) where each sub-model represents one level in the nitrate contamination process. In the economic sub-model, producers choose water and nitrogen fertilizer application rates to maximize profits. Results from the economic sub-model become input in the soil water solute transport sub-model which describes movement of water and nitrogen through the unsaturated or vadose zone of soil. Results from the soil water solute transport sub-model are input in the groundwater solute transport sub-model, which tracks loading and movement of nitrates throughout the study aquifer. This model is an outgrowth of the extensive groundwater studies preformed in the area because of its GMA status.

The integrated model is only summarized here with the greatest attention being given to the economic sub-model (for greater detail see ****, 1996). With the help of digitized USGS Soil Survey maps and other crop production maps, the study region is broken into 40 acre units. The 40 acre unit was chosen to conform with the needs of the groundwater solute transport sub-model. However, this is not believed to overly compromise the economic sub-model because average field size in the study region is 20 acres (Perry et. al., 1992). Using the soils maps, the soil type (subscript s in Equation 1) and corresponding crop mix (rotation) of each 40 acre unit is known. While up to five crops (wheat, onions, potatoes, sugar beets and hay; subscript c in Equation 1) can be grown in each unit (hence field sizes less than 20 acres), constraints are imposed that maintain the proper proportion of crops in each soil zone. This requires that constant returns to scale be assumed. Finally, all production units within a soil zone are treated as identical, based on information from OSU agricultural extension personnel (L. Jensen, personal communication, 1994).

In the economic sub-model, nitrogen input ($n_{c,s,t}$) and the crops to which this nitrogen is applied ($a_{c,s,t}$) are chosen to maximize profit (or net farm income) on 40 acres through time (Equation 1) subject to a series of production constraints (Equations 2 through 4) and rotation or crop mix constraints that are not shown. In Equation 1, λ^{sw} and λ^{gw} are the co-state or shadow values for soil water and groundwater nitrates, c^{sw} and c^{gw} are the state or stock values for soil water and groundwater nitrates, P is crop price, Q is crop yield, qadj is an adjustment to crop yield, np is nitrogen fertilizer price, cfc represents crop production fixed costs and r is the discount rate. In the production constraints, the parameter "can" is the county average nitrogen fertilizer application rate, cgrow is a matrix of 0 and 1 values that defines relevant crop-soil combinations and the parameter nac is the number of acres in a production unit. Note that c^{sw} and c^{gw} are functions of $n_{c,s,t}$ and $a_{c,s,t}$, but are calculated in, respectively, the soil water and groundwater solute transport sub-models.

$$\underset{n_{c,s,t}\ a_{c,s,t}\ \lambda^{sw}_{c,s,t}\ \lambda^{gw}_{i,j,t}\ c^{sw}_{c,s,t}\ c^{gw}_{i,j,t}}{Max\ \Pi} = \sum_{t=1}^{T} \left(\sum_{s=1}^{S} \sum_{c=1}^{C} [P_c Q(n_{c,s,t})_{c,s,t} qadj_c - (np \cdot n_{c,s,t}) - cfc_c] a_{c,s,t}\right) \frac{1}{(1+r)^t} dt \tag*{1.}$$

$$n_{c,s,t} \leq can_c \quad \forall\ c,s,t \tag*{2.}$$

$$a_{c,s,t} \leq cgrow_{c,s} * nac \quad \forall\ c,\ s,\ t \tag*{3.}$$

$$\sum_{c=1}^{C} a_{c,s,t} \leq nac \quad \forall\ s,\ t \tag*{4.}$$

In Equation 1, $Q(n_{c,s,t})$ is the crop yield-nitrogen response or production function. While an important component of the economic sub-model, available experimental data are, unfortunately, not adequate to estimate statistical nitrogen-yield relationships.

Furthermore, well established simulation models such as EPIC or CERES are not available for onions, potatoes and sugar beets. To circumvent this difficulty, quadratic production functions are assumed. This decision is based primarily on the fact that the available data suggest that the relationship between crop yield and nitrogen input is quadratic across all modeled crops.

Using county average nitrogen application rates (can) and county average crop yields (cay) as proxies for profit maximizing input and output levels, the first and second order terms (FOT and SOT) of a quadratic function can be determined. Specifically, by specifying the production function as $cay_{c,s} = FOT_{c,s}can_{c,s} - SOT_{c,s}(can_{c,s})^2$ and first order conditions for profit maximization as $P(FOT_{c,s} - 2\ SOT_{c,s}can_{c,s})qajd_c - np = 0$ both FOT and SOT can be solved for all crops on all soil types. The county level data used here are from the county in which the study region lies. Because mean values for crop yield and nitrogen fertilizer input are used, these production functions will lie below the "true" production function. However, these functions lie within the input requirement set for their respective crop and, as such, are feasible although not necessarily the economically or physically optimal level.

Given nitrate applications ($n_{c,s,t}$), the number of acres of each crop grown ($a_{c,s,t}$) from the economic sub-model and irrigation information, the soil water solute transport sub-model determines soil water and nitrogen leached. The soil water solute transport sub-model is based on the *Nitrogen Leaching Simulator* (NLEACH) Version 3.0 simulation model developed and validated by the department of Bioresource Engineering, Oregon State University (M. English, personal communication, 1995). NLEACH is a one-dimensional model, or alternatively, a plug-flow model that is capable of simultaneously modeling the movement of multiple nitrate-nitrogen pulses in soil. The NLEACH model preforms best on well drained, non-cracking soils under flood irrigation.

NLEACH calculates leached nitrogen and soil water for each crop on each soil type. This information is then used to determine the concentration (in ppm; c^{sw}) of nitrate leached for each 40 acre unit. Using the groundwater module of the simulation model, this nitrate is loaded into groundwater (c^{gw}), diluted and transported throughout the study region as groundwater flows toward the rivers bordering the region. Groundwater flow is modeled utilizing the finite difference method (Wang and Anderson, 1982) and it is assumed that only the mechanical process of groundwater flow (advection) is important.

An innovative aspect of this model is that it is capable of predicting ambient groundwater nitrate concentration throughout the aquifer and it directly links a producer's nitrogen input decision to spatial ambient groundwater nitrate concentration. Furthermore, given the region's GMA status, the ODEQ has designated a number of domestic and irrigation wells throughout the study region as monitoring wells, where groundwater nitrate levels are measured on a regular basis. Hence, predicted base (or starting point) groundwater nitrate concentration levels can be calibrated against observed levels.

Results

Estimating the impact of soil test information on producer profit and groundwater quality is accomplished in two steps. First, a base case set of results are established, given the assumption that soil testing is not conducted on any field in the study region. Next, the objective function is modified to capture how producers respond (with respect to their nitrogen input decisions) to soil test information. Because this model is dynamic, changes (reductions) in nitrogen input from soil testing is expected, in some future time period, to result in a new (lower) steady state equilibrium for residual soil nitrogen and groundwater nitrate concentration. At this new steady state equilibrium, test case results are recorded and compared to the base case results to measure the impact of the soil test information.

Base level predictions of groundwater nitrate concentration are similar to observed levels. Although the expressions in the groundwater solute transport sub-model smooth what in nature are widely varying concentration gradients, the model does a reasonable job of predicting both the level and variation in groundwater nitrate concentration. In the base case, differences between observed and predicted high concentrations at simulated observation wells ranged from -6.2 to 4.32 ppm with a mean difference of -1.4 ppm.

Table 1 reports results from the base and test case model runs. In Table 1, annual average per acre return is calculated by summing the ratio of total crop enterprise return to total acres of that crop grown across the crops grown on the different soil types. Base annual average return to producers in the region is $120 per acre. By crop, annual average per acre return is $451 for onions, $171 for potatoes, $133 for sugar beets, $66 for wheat and $38 for hay. These returns are in line with estimates reported in enterprise budgets published by Oregon State University’s Extension service. The per acre cost of crop production averaged $706 in the base case and producers applied on average 139 pounds of nitrogen per acre.

Historically, recommended nitrogen application rates have been 284 pounds on onions, 215 pounds on potatoes, 205 pounds on sugar beets and 136 pounds on wheat. Hence, an average per acre application of 139 pounds in the base case is in line with expectations. This application rate depends on what crops are grown and field size. These nitrogen application rates are consistent with the quantities of irrigation water applied (48 inches per acre annually) and with the high value of onions, potatoes and sugar beets.

Table 1. Results of soil testing in the study region.

	Base Case No Soil Test	Test Case Use Soil Test
Per Acre Return ($)	120.00	128.00 6.70[a]
Per Acre Cost ($)	706.00	698.00 -1.10[a]
Nitrogen Applied (lb/Ac)	139.00	98.00 -29.20[a]
Highest Simulated Groundwater Nitrate Concentration (ppm)	36.90	29.30 -21.60[a]

a) Percentage change from the base.

Accounting for soil test information increased annual per acre producer return 7 percent from the base. This increase in return was due to an $8.00 (1.1%) reduction in per acre total cost. Nitrogen applications were reduced on average 41 pounds per acre (29%). By crop, nitrogen applied to wheat was reduced 43%, sugar beets 35%, potatoes 19% and onions 10% from base levels. Since cost savings associate with reduced nitrogen application exceeded the cost, soil tests resulted in lower per acre total cost.

The highest predicted groundwater nitrate concentration measured at a simulated observation well was 36.9 ppm. The high rather than a mean predicted concentration is reported in Table 1 because compliance utilizing a mean concentration implies that some individuals may still be consuming potentially harmful levels of nitrate (Lee et. al., 1993). Soil testing all crop fields reduced the highest predicted groundwater nitrate concentration at a simulated observation well site 8 ppm (22%). Hence, the results of Table 1 can be summarized as follows. Soil testing allows producers to reduce nitrogen input sufficiently to cover the cost of the soil test. This reduction in nitrogen input improves both per acre producer return and groundwater quality.

Conclusions

Two conclusions are drawn from this investigation of soil test information. First, as demonstrated in previous works, the use of soil tests improves per acre return. However, the improvement in per acre return shown here is more modest relative to earlier investigations ($8 rather than $20 to $50 per acre). This improvement in per acre return is the result of nitrogen input cost savings, which exceed the cost of the fertilizer test.

The second conclusion is that soil testing all crop fields improves groundwater quality beneath the study region. Hence the impact of soil testing in the study region is an $8 increase in per acre return (from an $8 decrease in per acre cost) and an 8 ppm reduction in groundwater nitrate concentration. However, the more pertinent question is whether this reduction in groundwater nitrate concentration is sufficient to decrease the demand for direct regulation? The answer to this question, at least in the study region, is no. While model results indicate that "voluntarily" soil testing all fields will reduce the highest predicted groundwater nitrate concentration to 29.3 ppm, this concentration is still substantially greater than the 7 ppm concentration desired by the Oregon Department of Environmental Quality (the regulator in this case).

Soil testing all crop fields, while not solving the groundwater quality problem in the region, is a win-win alternative. Soil testing improves groundwater quality while improving farm profit. To meet the desired quality goal for the study region, additional technologies need to be evaluated and applied, agricultural production practices changed and (or) direct regulatory policies imposed. Additional technologies to be evaluated would include, for example, changes in irrigation application methods. It is also possible that the desired groundwater quality goal of 7 ppm is not obtainable (especially if this goal is to be achieved within the next few years) without great cost to producers.

The integrated assessment framework developed in this investigation is a comprehensive representation of a specific, complex problem, namely groundwater nitrate contamination. Without a representation of nitrate transport, such as used here, policy makers cannot evaluate the effect of technology change (for example, the use of a soil test) on groundwater quality. The results of study apply to hydrological regions with similar soil characteristics and shallow aquifers that discharge to streams or rivers. Note, however, that this model (and modeling approach) is transportable in the sense that parameter values can be respecified for use in other regions of the U.S.

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