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The Role of Soil Test Information in Reducing Groundwater Pollution

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Testing soils for nutrients is expected to improve groundwater quality. However, it is unknown whether soil testing will improve groundwater quality sufficiently to decrease the demand for direct regulation of agricultural practices. Focusing on an irrigated agricultural region in eastern Oregon, the economic and environmental aspects of soil testing are assessed using a spatially distributed, dynamic simulation model which links economic behavior with the physical processes that determine groundwater quality. Results indicate that soil testing of all fields increases farm profits and reduces groundwater nitrate concentration. However, the benefits are small in terms of potential improvements in groundwater quality.

Key words: dynamic modeling, economic impacts, groundwater, hydrology, nitrate, nitrogen fertilizer, soil test, water policy

Introduction

Soil tests provide information on the amount of nitrogen and other nutrients available for crop consumption. This information is valuable to producers if used to avoid the application of more nitrogen fertilizer than can be used by a crop. Eliminating excess fertilizer reduces crop production cost if fertilizer savings exceed the cost of soil testing. Reducing total fertilizer applications also may reduce the leaching of nutrients and improve groundwater quality. In agricultural regions with groundwater quality problems, producers may avoid environmental regulation by taking advantage of information that can lead to reductions in nutrient leaching and consequential improvements in groundwater quality.

Past studies have shown that soil test information can be valuable to producers. However, these studies tend to focus on cost savings, with little mention of the potential for improved groundwater quality. For example, Adams, Farris, and Menkhaus show that soil tests reduce nitrogen applications and improve per acre farm profit by $20 to $50 for sugar beets in Wyoming. A number of studies of Iowa, Nebraska, and Pennsylvania corn producers show that soil testing reduces average nitrogen fertilizer applications 15–41% while increasing per acre return (Babcock and Blackmer; Babcock, Carriquiry, and Stern; Fuglie and Bosch; Musser et al.). In an investigation of the Corn Belt, Lake States, and Northern Plains of the U.S., findings show a 25% reduction in

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nitrogen fertilizer reduced nitrate runoff and leaching while significantly increasing total net returns (Wu, Lakshminarayan, and Babcock).

The effect of soil testing on nitrogen applications is only an indicator of environmental performance (Musser et al.). Measuring actual environmental performance requires linking farm-level input decisions with ambient levels of an environmental contaminant. Because of the difficulty in linking nitrogen input decisions to groundwater nitrate concentration, to our knowledge no study has quantified changes in groundwater quality as a consequence of soil testing. While Babcock and Blackmer do not measure the value of changes in nitrate contamination of groundwater, they broach the possibility that soil testing may lower nitrogen applications sufficiently to decrease the likelihood of direct regulation.

The purpose of this analysis is to assess the potential for soil tests to improve ambient groundwater quality and producer profit. The efficacy of soil testing is assessed using a spatially distributed, dynamic simulation model which links changes in economic behavior as a result of soil testing with the physical processes that determine groundwater quality. By directly linking soil testing to ambient groundwater quality, we are able to examine the role of soil tests in reducing the demand for direct regulation.

Study Region, Groundwater Concerns, and Use of Soil Tests

The empirical focus is an irrigated agricultural region in Malheur County, Oregon. Located in eastern Oregon, this is a high desert environment; annual precipitation ranges from 5–16 inches, with an average of 10 inches. Irrigation is required for crop production, and surface (flood) irrigation is the principal method of application. The specific region evaluated in this investigation lies within the land area bounded by the Snake and Malheur Rivers and encompasses 32 square miles, of which 17,860 acres (28 square miles) are farmed.

While many crops (including fruit, vegetables, and seed crops) are grown here, 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 72% of regional crop acreage and 54% of total crop sales in 1992 [Malheur County Extension Service (MCES)]. Onions, potatoes, and sugar beets have a large impact on the economy in terms of jobs created by processing, handling, and field labor. Onions are the most valuable crop, accounting for 6% of regional acreage and 25% of crop sales in 1992.

Between August of 1988 and April of 1990, 199 wells were sampled; 32% had nitrate levels which exceeded the federal standard of 10 ppm for municipal water supplies. Because of these groundwater quality problems, the area was designated as a Groundwater Management Area (GMA) by the Oregon Department of Environmental Quality (ODEQ). This motivated several years of extensive data collection and analysis of geo-hydrologic conditions of the region.

An action plan was developed which relies on a voluntary approach to reduce nitrate concentrations through use of "best management practices." If nitrate levels at all monitoring wells do not reach 10 ppm by July 1, 2000, a regulatory approach with unstated mandatory action will be considered [Malheur County Groundwater Management Committee (MCGMC)].

Soil testing is identified in the plan as a method for reducing groundwater nitrate concentration. In response, the local Extension Service developed educational programs that encourage producers to test soils for nitrogen before applying fertilizer. These educational programs targeted onion and wheat producers. To date, 10% of the wheat fields and 80% of the onion fields are soil tested.

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 minor (or trace) nutrients. One sample is taken per field, where a sample consists of numerous random probes throughout the field.

A Programming Model of Soil Testing

While a conceptual model can provide insights into the potential impacts of soil testing, practical application of such a model is limited. For example, the impact of soil testing on groundwater quality is inferred, not specifically measured. Furthermore, the physical aspects of crop production and groundwater contamination are complex. Groundwater flow rates, the direction of groundwater flow, soils, crops grown, and crop production technology all vary across the region. Assessing the agronomic and environmental impacts of a policy that requires all fields to be tested for nitrogen requires a modeling approach capable of capturing these factors. A mathematical simulation or programming model that accounts for spatial linkages and variability in the physical parameters which determine groundwater quality is one means to assess the impact of soil testing on groundwater pollution.

Simulation or programming models which integrate geo-hydrology data with economic optimization models are commonly used to evaluate policies to control groundwater quality (Johnson, Adams, and Perry; Mapp et al.; Chowdhury and Lacewell). The integrated model developed here is a spatially distributed, dynamic simulation model and consists of three submodels: (*a*) economic, (*b*) soil water solute transport, and (*c*) groundwater solute transport. In the economic submodel, producers choose nitrogen fertilizer application rates to maximize profits subject to production constraints and assumptions concerning residual soil nitrogen. Results from the economic submodel become input parameters in the soil water solute transport submodel, which describes movement of water and nitrogen through the unsaturated or vadose zone of soil. This submodel also measures the level of residual soil nitrogen used in the economic submodel in the next period. Results from the soil water solute transport submodel become input parameters in the groundwater solute transport submodel, which tracks loading and movement of nitrates in the aquifer. With this last model, changes in optimal nitrogen input levels due to soil test information can be linked to changes in spatial groundwater nitrate concentration. This latter model component is an outgrowth of the extensive groundwater studies preformed in the area because of its GMA status.

The Economic Submodel

Equations (1), (14), and (15) below are the primary, formal mathematical expressions of the model. Within this set of equations, equation (1) defines the economic submodel. Specifically, 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) through time, subject to a level of residual soil nitrogen ($rsn_{c,s,t}$) that is measured or assumed and a series of production constraints. The production constraints are used to limit total nitrogen [equation (2)], fix maximum yield [equation (3)], restrict crop acreage [equation (4)], and determine crop rotation [equations (7)–(12)]. Onions, potatoes, and sugar beets are high-value crops, but with high yield and revenue variance. Hence, crop rotations arise as a result of crop diversification. Crop rotations also are used for weed, disease, and crop pest control, and as a form of nutrient management. Finally, because the model must account for crop rotations through time, both current-period and cross-period [equations (5) and (6)] crop acreage restrictions are necessary.

The economic submodel is specified in equations (1)–(12) below:

(1) Maximize the objective function,

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

subject to the following production constraints:

(2) $$n_{c,s,t} + rsn_{c,s,t} = ntot_{c,s,t} \le n\max_{c,s} \quad \forall\ c, s, \text{ and } t,$$

(3) $$Q\left(ntot_{c,s,t}\right)_{c,s,t} \le cay_{c,s} \quad \forall\ c, s, \text{ and } t,$$

(4) $$a_{c=w,s,t} + a_{c=o,s,t} + a_{c=p,s,t} + a_{c=s,s,t}\, a_{c=h,s,t} \le 40 \quad \forall\ s \text{ and } t,$$

(5) $$a_{c=o,s,t-1} + a_{c=p,s,t-1} \le a_{c=w,s,t} + a_{c=s,s,t} + a_{c=h,s,t} \quad \forall\ s \text{ and } t,$$

(6) $$a_{c=o,s,t} + a_{c=p,s,t} \le a_{c=w,s,t-1} + a_{c=s,s,t-1} + a_{c=h,s,t-1} \quad \forall\ s \text{ and } t,$$

(7) $$a_{c=o,s,t} + a_{c=p,s,t} \le a_{c=w,s,t} + a_{c=s,s,t} \quad \forall\ s \text{ and } t,$$

(8) $$a_{c=o,s,t} \le a_{c=p,s,t} \quad \forall\ s \text{ and } t,$$

(9) $$a_{c=s,s,t} \le a_{c=w,s,t} \quad \forall\ s \text{ and } t,$$

(10) $$0.25\,a_{c=w,s=A,t} \le a_{c=h,s=A,t} \quad \forall\ t,$$

(11) $$a_{c=w,s=C,t} + a_{c=s,s=C,t} \le a_{c=h,s=C,t} \quad \forall\ t,$$

and

$$(12)\qquad 0.25\left(a_{c=w,s=D,t} + a_{c=s,s=D,t}\right) \le a_{c=h,s=D,t} \quad \forall\, t.$$

The crop rotation constraints used here yield soil-specific crop mixes consistent with those observed prior to 1990 (when the area was listed as a Groundwater Management Area). More importantly, without these constraints, the model would not "grow" potatoes on onion/potato acreage, and wheat and hay would not be "grown" on sugar beet/wheat/hay acreage because these crops are less valuable. Also, nitrogen input is restricted to avoid an unbounded solution [equation (2)].

Common symbols across all equations include the c subscript, which denotes crop type (w = wheat, o = onions, p = potatoes, s = sugar beets, and h = hay); s, which represents the various production units differentiated by soil type (soil groups A, B, C, and D); and t, time. 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 resulting from storage losses, np is nitrogen fertilizer price, cfc represents crop production fixed costs, IC is information cost (cost of the soil test), and r is the discount rate. In equation (2), $ntot_{c,s,t}$ is the total amount of nitrogen (applied nitrogen $n_{c,s,t}$, and residual soil nitrogen $rsn_{c,s,t}$) available for crop consumption. Total available nitrogen ($ntot_{c,s,t}$) cannot exceed $n\max_{c,s}$, the maximum amount of nitrogen needed to maximize crop yield. In equation (3), $cay_{c,s}$ is crop yield.

The agricultural sector consists of a large number of producers who use nitrogen fertilizer to produce the five major crops grown in the area. Soils in the study region are grouped into four general classifications, and each soil grouping produces a different mix of crops. Specifically, soil group A is planted mainly to wheat and hay (because of slope), soil group B is planted predominately to row crops (onions, potatoes, and sugar beets in rotation with wheat), soil group C is planted predominately to wheat, sugar beets, and hay (because of poor drainage), and soil group D is planted to wheat, potatoes, and hay. Differences in slope and soil type limit the productivity of onions, potatoes, and sugar beets on some soils. Hence, shifting crops to different soils as a strategy to reduce nitrogen losses is not practical. Finally, the soil zones are geographically contiguous and sloped such that groundwater from A flows through B to soil zones C and D, where it is discharged to the Snake (the east border of soil zones C and D) and the Malheur (the norther border of soil zone C) Rivers.

The basic building block in the groundwater solute transport submodel is a 40-acre "production unit" around which the economic submodel is constructed. Specifically, "representative" farms of 360 acres are composed of nine production units of similar soil type.[1] All representative farms within a given soil zone are treated as identical (i.e., same-crop alternatives, management strategies, production technology, input use, returns, and costs), based on information from agricultural extension personnel. While each production unit within a soil zone is uniform with respect to production and soil water concentration (mentioned below), groundwater nitrate concentration beneath each can vary significantly.

[1] The average farm size in the study region is 365 acres (Perry, Fleming, and Conway).

Crop yield-nitrogen response (production) functions [$Q(ntot_{c,s,t})_{c,s,t}$ in equation (3)] are an important component of the economic submodel. Unfortunately, experimental data are not adequate to estimate statistical nitrogen-yield relationships for the study area, and well-established simulation models such as EPIC or CERES were not available for onions, potatoes and sugar beets at the time of this investigation.

There is considerable debate concerning what constitutes an appropriate fertilizer response function. Griffin, Montgomery, and Rister, in their review of different functional forms, conclude that none of the many selection criteria guarantee that the true relationship will be discovered, nor do any allow a totally objective choice to be made. Some researchers argue that the response is a smooth, concave function, while others contend that the correct function is the linear response and plateau (LRP) or von Liebig model (Berck and Helfand). Berck and Helfand, while noting that the two functional forms are not mutually exclusive, conclude that aggregating across fields (as is done in this investigation) results in a response curve where yield is a smooth, concave function of nitrogen input.

Many functional forms, including the quadratic, are smooth, concave functions. An advantage of the quadratic function is that known endpoints can be used to mathematically derive the curve (Debertin; Fleming and Adams). However, some researchers object to the use of a smooth, concave function given that yields of some crops do not decrease with added nitrogen, as suggested by a concave production function (Babcock). Furthermore, uncertainty about growing conditions translates into uncertainty about the yield plateau and the amount of nitrogen at which this plateau is achieved. A smooth, concave function is ill suited to account for this uncertainty.

The nitrogen-yield functions used here are LRP, similar to those proposed by Babcock. Uncertainty in residual soil nitrogen [$rsn_{c,s,t}$ in equations (1), (2), and (13)] is incorporated in the function. This uncertainty is not expected to impact the plateau (maximum) yield. Specifically, without a soil test, the producer must guess how much nitrogen is provided by soil, and then supplement with commercial nitrogen. In practice, producers monitor crop yields. If yields are low, then they infer that their estimate of *rsn* is too high; hence they lower their expectations and apply more nitrogen in the next year. Over time, producers come to "understand" their soils. However, for high-value crops like onions, the revenue loss associated with a small reduction in yield due to insufficient nitrogen induces growers to apply excess nitrogen.

Following Babcock, crop yield ($Q_{c,s,t}$) is a linear function of total available nitrogen ($ntot_{c,s,t}$) up to some maximum yield, after which yield is constant [equation (13)]. Here it is assumed that the soil-specific, long-run county average yield (*cay*) for any crop reflects the profit-maximizing yield. Given the "kinked" shape of the LRP production function, with nonlimiting factors, profit will be maximized at the kink. Hence, the maximum yield is also the profit-maximizing yield, which is assumed to be the county average yield in this model. Long-run county average yields were obtained from the Malheur County offices of the Farm Services Administration and the Natural Resource Conservation Service (table 1).

From the intercept to $cay_{c,s}$, crop yield ($Q_{c,s,t}$) is a linear function of total available nitrogen ($ntot_{c,s,t}$). All the LRP functions pass through the origin. From the origin, then, increased total available nitrogen increases crop yield. When crop yield reaches the county average ($cay_{c,s}$ at the "kink"), total available nitrogen is equal to maximum required nitrogen ($n\max_{c,s}$). Further applications of nitrogen are possible, but yield will

Table 1. Crop Production Data and Model Parameters

Model Parameters / Crop	Soil Zone A	Soil Zone B	Soil Zone C	Soil Zone D
Average Yield (*cay*):				
▸ Wheat	109	125	106	111
▸ Onions	—	625	—	—
▸ Potatoes	—	405	—	380
▸ Sugar Beets	—	31	27	—
▸ Hay	5	6	4	5
Nitrogen Leached (*SoilNL*):[a]				
▸ Wheat	15	52	28	27
▸ Onions	—	143	—	—
▸ Potatoes	—	94	—	68
▸ Sugar Beets	—	51	28	—
Slope Coefficient (β):[b]				
▸ Wheat	0.482	0.437	0.465	0.466
▸ Onions	—	1.900	—	—
▸ Potatoes	—	1.535	—	1.640
▸ Sugar Beets	—	0.088	0.091	—
Maximum N (*n*max) to Produce *cay*:				
▸ Wheat	226.3	286.1	228.0	238.1
▸ Onions	—	329.0	—	—
▸ Potatoes	—	263.8	—	231.7
▸ Sugar Beets	—	353.9	296.1	—

	Region Crop Data			
	Wheat	Onions	Potatoes	Sug. Beets
High Yield (*YMax*)[c]	174	1,017	626	51
Crop N Uptake (*cnu*) at *YMax*[c]	277	314	251	425

Note: The computer package GAMS calculates values to the 13th digit. Hence, there can be rounding error for β using the values in this table.

[a] Derived from Fleming (p. 100).

[b] Percent nitrogen lost to surface wind and water erosion (*%SurfNL*) is 25% (Fleming, p. 57).

[c] Summarized from Malheur Experiment Station data reported in Fleming (pp. 191–203).

not change. Maximum required nitrogen is derived mathematically: $n\max_{c,s}$ is equal to $cay_{c,s}$ divided by $\beta_{c,s}$, the slope of the yield-nitrogen (production) function prior to the plateau [equation (13) and table 1].

The slope term ($\beta_{c,s}$) is derived from experimental and simulation data (Fleming) (table 1). Specifically, $\beta_{c,s}$ is the experimentally measured maximum crop yield (*YMax*) divided by the quantity of nitrogen needed to obtain that yield [equation (13)]. Unfortunately, crop nitrogen uptake (*cnu*), not the quantity of nitrogen needed, is measured. However, mass balance (from soil physics) requires that the quantity needed equals crop uptake (*cnu*) plus that lost to surface wind and water erosion (*%SurfNL*) and deep percolation (*SoilNL*). Quantities for leached nitrogen (from deep percolation) were obtained from simulation data using the crops and soils in the study region (Fleming) (table 1). Simulation data were used because soil mineralization[2] and leached nitrogen were measured as a residual in the experimental data.

Equation (13) specifies the crop yield-nitrogen response (production) functions of the economic submodel:

$$(13)\quad Q_{c,s,t} = \beta_{c,s} ntot_{c,s,t} = \beta_{c,s}(n_{c,s,t} + rsn_{c,s,t}) \quad \text{for } 0 \le ntot_{c,s,t} \le n\max_{c,s},$$

$$= Q\max_{c,s} = cay_{c,s} \quad \text{for } ntot_{c,s,t} > n\max_{c,s},$$

$$n\max_{c,s} = \frac{cay_{c,s}}{\beta_{c,s}},$$

$$\beta_{c,s} = \frac{Y\mathrm{Max}_c}{cnu_c\left(1 + \dfrac{\%SurfNL}{100}\right) + SoilNL_{c,s}}.$$

While the slope of the production function in equation (13) is from physical data, the plateau of this function is for profit-maximizing yield ($cay_{c,s}$). This "adjustment" is necessary because the profit-maximizing solution is an interior corner-point. These production functions represent the regional response, not the frontier function, of an individual producer. Crop production technology is fixed through time (although technology, e.g., the type of irrigation system, does vary across soils in the model). The producer has flexibility with respect to nitrogen input and crop choice.

Regional crop enterprise budgets from the Oregon State University Extension Service were used to determine per acre crop production fixed costs [*cfc* in equation (1)]. Field and farm sizes are consistent with those assumed in the crop enterprise budgets, since enterprise fixed costs (which include, among other things, a machinery complement) are calculated for a specific field size. These budgets are based on best management practices; hence they may overstate fixed costs because area average yields are used. Constant returns to scale are assumed for each crop. The cost of testing soil for nitrogen [*IC* in equation (1)] is also fixed ($15 per field). Depending on field size, the per acre cost of soil testing ranges from $0.47 to $1.50 annually. For wheat and onions, where soil tests are not the norm, *IC* is initially set to zero.

The Soil Water and Groundwater Solute Transport Submodels

The soil water solute transport submodel determines leached soil water and nitrogen, given nitrate applications ($n_{c,s,t}$), the number of acres of each crop grown ($a_{c,s,t}$) from the economic submodel, and irrigation information. This submodel is based on the Nitrogen Leaching Simulator (NLEACH), version 3.0 simulation model developed in the Department of Bioresource Engineering, Oregon State University, to investigate the dynamics of nitrogen in irrigated soils (English). NLEACH is a one-dimensional, mass balance

[2] Mineralization is a generalized category for actual mineralization, immobilization, denitrification, and volatilization that can be positive or negative. If mineralization is negative, then losses to immobilization, denitrification, and volatilization are greater than the gains from actual mineralization.

model that simulates the movement and transformation of nitrate-nitrogen in an irrigated crop system. This model is based on commonly accepted principles of nitrogen dynamics without adjustments for unique features of soil or the crop (Mills; Rao, Davidson, and Hammond).

Pulses of soil nitrogen are tracked by the soil water solute transport submodel to a depth of 48 inches. For potatoes and sugar beets, the historic mean crop yield (the plateau or profit-maximizing yield) reflects the long-time use of soil tests. For potatoes, a soil test is assumed to measure the nitrogen in the top foot of soil. Specifically, the simulated content of nitrogen in soil no more than 12 inches deep at the start of the growing season is summed and assigned to the variable residual soil nitrogen [$rsn_{c,s,t}$ in equations (1), (2), and (13)]. The process is similar for sugar beets, but nitrogen in the top two feet of soil is measured. Historically, onion and wheat fields were not soil tested. For these crops, the producer makes an informed guess concerning the value of $rsn_{c,s,t}$. Note that $rsn_{c,s,t}$ is exogenous to the optimization problem in the economic submodel regardless of whether it is estimated by the soil water submodel or guessed.

Equations (14) and (15) comprise the groundwater solute transport submodel:

$$(14) \qquad c^{lgw}_{i,j,t,t_c} = c^{gw}_{i,j,t,t_c} + \left(\frac{wl_{i,j,t}}{deep \times n_a \times 12}\right)\left(\frac{dt_c}{365} c^{sw}_{i,j,t} - c^{gw}_{i,j,t,t_c}\right);$$

$$(15) \qquad c^{gw}_{i,j,t,t_c+dt_c} = c^{lgw}_{i,j,t,t_c} - \frac{dt_c VI_{i,j}}{n_a di}\left(c^{lgw}_{i,j,t,t_c} - c^{lgw}_{i+di,j,t,t_c}\right) - \frac{dt_c VJ_{i,j}}{n_a dj}\left(c^{lgw}_{i,j,t,t_c} - c^{lgw}_{i,j-dj,t,t_c}\right).$$

Leached nitrogen and soil water from NLEACH (in the pulses that reach 48 inches in depth) are converted to a concentration in parts per million (ppm or milligrams per liter). In equation (14), c^{lgw} is the concentration of nitrate in groundwater after loading, c^{gw} is the concentration of nitrate in groundwater before loading, c^{sw} is soil water nitrate concentration, wl is the depth of soil water leached (in inches), *deep* is the depth of the aquifer (in feet), and n_a is porosity or actual pore space containing groundwater. Groundwater nitrate concentration, hence nitrate loading, is calculated every five (dt_c) days.

The geo-hydrology model is based upon the work of Walker. Groundwater flow is modeled utilizing a mesh of grid points superimposed over a map of the study region. Each grid point is centered in a 40-acre production unit. Also, each point is characterized by a set of physical and production data (for the production unit) that is used to calculate groundwater nitrate concentration.

Nitrates in groundwater [equation (14)] are transported throughout the study region. It is assumed that (*a*) nitrogen is not chemically bound by soil, (*b*) nitrogen does not chemically decay through time, and (*c*) nitrogen (through a chemical process called dispersion) does not move upstream against the flow of groundwater. These assumptions give rise to equation (15), the reduced discrete form of the fully explicit finite difference expression [for groundwater velocities in the i and j directions ($VI_{i,j}$ and $VJ_{i,j}$) ≥ 0].

Equation (15) is used to solve for groundwater nitrate concentration at each production unit.[3]

Procedures

The integrated simulation model is constructed around the 40-acre production unit because this area was deemed sufficiently small to measure changes in groundwater nitrate concentration every five "days." With equation (15), groundwater nitrate concentration is estimated (or predicted) at every production unit in the study region. Because the model is dynamic, a rule was needed to determine when to stop. Specifically, the simulation ends when the annual change in groundwater nitrate concentration across all cells is less than 0.3 ppm; this is the steady state . Furthermore, the locations of wells in the region used to monitor groundwater nitrate levels are known. From these data, specific production units are identified as monitoring wells in the simulation and used to predict groundwater nitrate concentrations (high, average, and low values for a soil zone or the region) in tables 2–4.

Estimating the impact of soil testing on producer profit and groundwater quality is accomplished in two steps. First, base case results are established assuming pre-1990 conditions, where only sugar beet and potato fields are soil tested. Residual soil nitrogen (RSN) for wheat and onions is fixed, respectively, at 100 pounds and 30 pounds per acre. The base simulation starts with no nitrogen in the soil profile and a pristine aquifer. From this pristine state, regional economic and geophysical data are compiled, and simulated agricultural production begins. In time, steady-state soil water and groundwater nitrate concentrations are reached and base case results measured.

Next, starting with base case levels, "test case" results are estimated. Here all modeled fields, including onion and wheat fields, are soil tested. The expected consequence of soil testing all crop fields is that new (lower) steady-state soil water and groundwater nitrate concentrations are achieved. Base case and test case results are then compared to determine the impact of additional soil testing on producer profit and groundwater nitrate concentration.

The results of the base case depend on the assumption that soil provides 100 pounds and 30 pounds of nitrogen per acre to wheat and onions, respectively. To test the sensitivity of results to changes in assumed soil nitrogen, three additional scenarios were tested. In the first, an extreme case is tested where it is assumed that soil does not provide residual nitrogen to wheat and onions. In the second scenario, RSN available to wheat and onions is decreased 20 pounds per acre from base levels (wheat 80 pounds/acre and onions 10 pounds/acre). In the third scenario, available RSN is the same for wheat and onions (60 pounds/acre). For each scenario, test case (all fields soil tested) results are estimated. All model runs were compiled using the General Algebraic Modeling System (GAMS) release 2.25 solver.

[3] Two simplifications are made to maintain tractability. First, the only source of groundwater nitrates is nitrogenous inputs to crop agriculture. Second, the quantity, timing, and rate of soil water flow (hence the amount of soil water leached) are fixed. This is accomplished by fixing irrigation technology, irrigation management (application rate and scheduling), and climatic variables through time. The second assumption implies steady-state flow, which reduces computational time.

Results

Base Case Results

The results for the base case are reported in table 2. In general, the model performed adequately in terms of replicating key hydrologic endpoints. Groundwater movement is from soil zone A, through B, to soil zones C and D; the rate of groundwater flow slows dramatically beneath soil zone B. These spatial heterogeneities in the rate and direction of groundwater flow account for the reported differences in groundwater nitrate concentration across the region. Excluding soil zone C, predicted mean concentrations are nearly equal to the observed mean. In soil zone C, the observed mean is 8 ppm greater than predicted. Predicted high concentrations tend to be less than observed levels (by 7 ppm on average). The model accounts for much of the spatial variation in nitrate concentration in soil zones A and D, and less so in soil zones B and C.

Table 2 reports both the high and mean predicted groundwater nitrate concentration across simulated observation well sites for the region and individual soil zones. The high concentration is reported because a mean concentration implies that some individuals still may be consuming potentially harmful levels of nitrates even if groundwater quality meets the target level of 10 ppm (Lee, Howitt, and Marino). Highest predicted groundwater nitrate concentrations occur beneath soil zones B and D (both exceed 20 ppm) due to slow groundwater flow rates and the production of onions and potatoes. Soil zone C also has high groundwater concentrations (15 ppm), but water quality in soil zone A is good. For the region, both the high and mean concentrations exceed the standard set by the Oregon Department of Environmental Quality (7 ppm). None of the production units in soil zone A had an underlying groundwater nitrate concentration in violation of the federal standard (10 ppm; see table 2). However, 74%, 12%, and 87% of the production units in soil zones B, C, and D, respectively, were in violation, resulting in an overall regional compliance rate of 45%.

With respect to base case crop production, the model estimates average per acre return to be $637 for onions, $266 for potatoes, $178 for sugar beets, $40 for wheat, and $27 for hay. These returns are consistent with published data.[4] Acreage in wheat and onions ranges from 25–80% across the soil zones, with 47.5% of regional acreage in these crops (table 2). Producers apply 147 pounds of nitrogen to wheat crops and 299 pounds to onion crops. Average nitrogen application rates (across crops) within a soil zone range from 77–223 pounds per acre, with a mean of 155 pounds. These estimates are consistent with current application rates of 284, 215, 205, and 136 pounds per acre, respectively, for onions, potatoes, sugar beets, and wheat.

In table 2, results for average per acre return (across the crops) and yield are reported as "modeled" and "tested RSN." The modeled return and yield is what the producer will receive if the assumed levels of residual soil nitrogen (here 100 pounds and 30 pounds for wheat and onions, respectively) are correct. The tested RSN return and yield are what the producer actually receives based on predicted levels of residual soil nitrogen. If modeled (anticipated) soil nitrogen levels equal tested levels, then average per acre returns are the same (as is yield).

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[4] Oregon State University's Extension Service publishes enterprise budgets for many crops grown in the region. Estimates of per acre crop return for the yields and prices used in this study are $429 for onions, $322 to $152 for russet potatoes, $152 to $59 for sugar beets, and $103 to $54 for wheat. Enterprise budgets for hay are not available.

Table 2. Base Case Results: Crop Acreage, Farm Income, Crop Yield, Nitrogen Use, and Groundwater Quality

Description	Soil Zone A	Soil Zone B	Soil Zone C	Soil Zone D	Region (Total or Mean)
Acreage[a]	3,620	8,520	4,400	1,320	17,860
% of Acreage in:					
▸ Wheat	80	25	25	40	37
▸ Onions	—	25	—	—	12
Per Acre Return ($):					
▸ As Modeled	55	311	41	110	178
▸ Tested RSN	-1	302	35	72	158
Wheat Yield (bu./acre):					
▸ As Modeled	109	125	106	111	114
▸ Tested RSN	87	113	98	81	97
Onion Yield (cwt/acre):					
▸ As Modeled	—	625	—	—	625
▸ Tested RSN	—	625	—	—	625
N Required (lbs./acre):					
▸ Average	181	308	131	188	230
▸ Wheat	226	286	228	238	247
▸ Onions	—	329	—	—	329
N Applied (lbs./acre):					
▸ Average	102	223	77	104	155
▸ Wheat	126	186	128	138	147
▸ Onions	—	299	—	—	299
Residual N (lbs./acre):[b]					
▸ Average	44	84	52	60	66
▸ Wheat	55	74	82	37	64
▸ Onions	—	53	—	—	53
Soil Nitrogen Leached (ppm)	6.2	21.1	2.8	20.6	13.5
Groundwater Quality:					
▸ High N Concentration (ppm)					
- Observed	8.1	31.0	32.9	14.4	32.9
- Predicted	3.4	20.5	15.0	20.6	20.6
▸ Mean N Concentration (ppm)					
- Observed	2.7	12.8	12.2	14.2	11.0
- Predicted	2.4	13.7	4.3	14.9	8.7
▸ % Nodes above 10 ppm	0	74	12	87	45

Note: Potatoes and sugar beets, not wheat and onions, are soil tested, and it is assumed that wheat and onions utilize 100 pounds and 30 pounds, respectively, of residual soil nitrogen (RSN).

[a] Total acreage by crop: wheat = 6,654 acres, onions = 2,130 acres, potatoes = 2,658 acres, sugar beets = 3,230 acres, and hay = 3,188 acres.

[b] Includes sugar beets, where residual soil nitrogen (RSN) is measured to 24 inches.

Across the soil zones, tested per acre return is less than modeled (table 2). For the region, tested return is $158 per acre, $20 less than modeled (expected), due to an average yield loss in wheat of 17 bushels per acre. Specifically, soil was anticipated to provide 100 pounds of nitrogen, but actually provided much less (26–63 pounds less), resulting in reduced wheat yields. Onion yields were not affected; more residual nitrogen than anticipated was provided by soil. However, excess nitrogen was applied to onions, resulting in a lower per acre return. Finally, per acre return is greatest in soil zone B because of the high-valued crops grown here. This, and the fact that there is more acreage in soil zone B, inflates regional per acre return. At $158, tested per acre regional return is $86 to $159 larger than tested returns in soil zones A, C, and D.

Impact of Mandatory Soil Testing

With soil testing, modeled and tested RSN returns are identical, as are yields (table 3). The use of soil tests on wheat and onion fields decreased modeled regional per acre return $3, but increased tested per acre return $17 (compare tables 2 and 3). With soil testing, per acre return across the soil zones is $2 to $7 less than modeled return in the base case. This reduction is due to the cost of soil testing and the fact that insufficient nitrogen is applied in the base model. However, soil testing increased per acre returns $5 to $49 relative to tested RSN returns. This increase is due to improved nutrient management that improves yield. Specifically, wheat yields are increased 17 bushels per acre from tested (actual) yields in the base case. Furthermore, the cost savings associated with these yield gains exceed the cost of the fertilizer test ($15 per field).

One surprising result is that soil testing increases applied nitrogen (compare tables 2 and 3). While nitrogen applications to onions are reduced 25 pounds per acre, applications to wheat are increased 35 pounds, resulting in a regionwide average increase of nine pounds per acre. With soil testing, the economically efficient level of nitrogen is achieved, which is higher than the base case. The increased expenditures on nitrogen are offset by the revenue gains associated with increased yields.

Although nitrogen use is increased relative to the base scenario, groundwater quality is slightly improved. With higher yields, more nitrogen is taken up (consumed) by the crop. Specifically, better nutrient management allows the crop to produce more (and deeper) roots which take up more nitrogen. Here, more efficient nitrogen use offsets the increase in applied nitrogen and the slight increase in residual soil nitrogen and reduces the amount of nitrogen being leached to groundwater, i.e., leached nitrate is reduced 1–6 ppm across the soil zones for an average reduction of 3 ppm (compare tables 2 and 3). This reduction in leached nitrate reduces the high and mean predicted levels of groundwater nitrate concentration by approximately 2.1 ppm. Furthermore, the percentage of fields with groundwater in violation of the federal drinking water standard is reduced from 45% to 36%.

Sensitivity Analysis

A set of sensitivity scenarios was estimated to measure the degree to which model results change under alternative levels of residual soil nitrogen. Table 4 reports the results of the three sensitivity model runs. For the base case and sensitivity scenarios, separate test case scenarios (where all crops are soil tested) were estimated. The test

Table 3. Soil Testing Results: Crop Acreage, Farm Income, Crop Yield, Nitrogen Use, and Groundwater Quality

Description	Soil Zone A	Soil Zone B	Soil Zone C	Soil Zone D	Region (Total or Mean)
Acreage [a]	3,620	8,520	4,400	1,320	17,860
% of Acreage in:					
▸ Wheat	80	25	25	40	37
▸ Onions	—	25	—	—	12
Per Acre Return ($)	48	309	40	104	175
Wheat Yield (bu./acre)	109	125	106	111	114
Onion Yield (cwt/acre)	—	625	—	—	625
N Required (lbs./acre):					
▸ Average	181	308	131	188	230
▸ Wheat	226	286	228	238	247
▸ Onions	—	329	—	—	329
N Applied (lbs./acre):					
▸ Average	131	226	79	129	164
▸ Wheat	163	217	145	222	182
▸ Onions	—	274	—	—	274
Residual N (lbs./acre): [b]					
▸ Average	51	82	52	60	67
▸ Wheat	64	69	83	16	65
▸ Onions	—	55	—	—	55
Soil Nitrogen Leached (ppm)	0.0	19.2	1.6	14.8	10.6
Predicted Groundwater Quality:					
▸ High N Concentration (ppm)	0.0	18.5	13.3	14.8	18.5
▸ Mean N Concentration (ppm)	0.0	11.1	3.2	10.4	6.6
▸ % Nodes above 10 ppm	0	63	6	54	36

[a] Total acreage by crop: wheat = 6,654 acres, onions = 2,130 acres, potatoes = 2,658 acres, sugar beets = 3,230 acres, and hay = 3,188 acres.
[b] Includes sugar beets, where residual soil nitrogen (RSN) is measured to 24 inches.

case results are not sensitive to changes in assumed residual soil nitrogen levels. As shown in column 4, table 4, the test case results are identical.

In all cases, model returns were less than or equal to tested (or actual) returns (table 4). An unreported supplementary analysis shows that if all producers in the region accurately predicted residual soil nitrogen levels without the aid of a soil test, average return is $175.50 per acre. With soil testing, average return is $174.94 per acre; hence the average cost of requiring all producers in the region to soil test is $0.56 per acre. However, this cost is spread across potato and sugar beet acreage that is already soil tested. The average cost of producing wheat and onions in the study region is increased by $1.13 per acre when these crops are required to be soil tested.

Assuming no residual nitrogen (scenario 1) also resulted in modeled and tested returns that were equal (table 4). This is the "conservative" or risk-minimizing strategy because a producer ignores soil nitrogen and applies sufficient nitrogen to guarantee

Table 4. Sensitivity Analysis: Crop Acreage, Farm Income, Crop Yield, Nitrogen Use, and Groundwater Quality for the Region

Description	Scenario [a]			
	1	2	3	4
Per Acre Return ($):				
▸ As Modeled	170	178	175	175
▸ Tested RSN	170	158	169	175
Wheat Yield (bu./acre):				
▸ As Modeled	114	114	114	114
▸ Tested RSN	114	97	113	114
Onion Yield (cwt/acre):				
▸ As Modeled	625	625	625	625
▸ Tested RSN	625	625	616	625
N Required (lbs./acre):				
▸ Average	230	230	230	230
▸ Wheat	247	247	247	247
▸ Onions	320	329	329	329
N Applied (lbs./acre):				
▸ Average	191	155	193	164
▸ Wheat	247	147	187	182
▸ Onions	329	299	269	274
Residual N (lbs./acre): [b]				
▸ Average	76	66	67	67
▸ Wheat	81	64	67	65
▸ Onions	46	53	55	55
Soil Nitrogen Leached (ppm)	16.2	13.5	11.4	10.6
Predicted Groundwater Quality:				
▸ High N Concentration (ppm	27.4	20.6	19.2	18.5
▸ Mean N Concentration (ppm)	10.7	8.7	7.1	6.6
▸ % Nodes above 10 ppm	49	45	37	36

Note: There are 17,860 total crop acres in the region: wheat = 6,654 acres (37%), onions = 2,130 acres (12%), potatoes = 2,658 acres (15%), sugar beets = 3,230 acres (18%), and hay = 3,188 acres (18%).

[a] Scenario Descriptions:

1 = The extreme case where wheat and onions are not soil tested and it is assumed that wheat and onions do not utilize residual soil nitrogen.

2 = The base case where wheat and onions are not soil tested and it is assumed that wheat and onions utilize 100 pounds and 30 pounds of residual soil nitrogen, respectively.

3 = A sensitivity scenario where wheat and onions are not soil tested and it is assumed that wheat and onions utilize 60 pounds of residual soil nitrogen. At the regional level, these results are nearly identical to assuming that wheat and onions utilize 80 pounds and 10 pounds of residual soil nitrogen, respectively.

4 = The test case where all crops are soil tested.

[b] Includes sugar beets, where residual soil nitrogen (RSN) is measured to 24 inches.

optimal yield. In this case, nitrogen is overapplied and returns are reduced $5 per acre. But this loss is less than the $6 to $17 actual loss reported in the other scenarios. In fact, scenario 1 behavior is observed in many of the high-valued cropping regions of Oregon and Washington. Such behavior will remain common as long as nitrogen is relatively inexpensive (Johnson, Adams, and Perry).

Changes in the assumed level of residual soil nitrogen (RSN > 0) have some impacts on production and profits, but little effect on groundwater quality (compare columns 2 and 3, table 4). Groundwater quality results were most sensitive to the case where residual soil nitrogen is ignored (scenario 1). Here, substantially more nitrogen is applied to wheat and onions, and average residual soil levels increase. Potatoes and sugar beets benefit from this increase (this is why the average application is less than that in column 3), but increased consumption of nitrogen by these crops is not sufficient to prevent groundwater damage, as the high predicted concentration is increased at least 7 ppm.

Summary of Results

A key finding of this analysis is that requiring all fields in the study region to be soil tested improves groundwater quality. However, soil tests are not sufficient by themselves to meet Oregon's quality target of 7 ppm for nitrate based on highest predicted concentration (not mean concentration) (Lee, Howitt, and Marino). This is true even though the predicted high groundwater nitrate concentrations in the base case are substantially less than observed (table 2). Soil testing thus has limited potential as a policy tool in that such tests are not likely to reduce the demand for direct regulation.

In addition to improving groundwater quality, soil testing has the added benefit of increasing modeled producer profit. While this win-win situation is desirable, this result does raise the question of why wheat and onion fields are not currently soil tested if doing so is profitable. The roles of education and risk attitudes, which could play a major role in a producer's decision to utilize soil test information, are not included in this analysis. Requiring that all fields be soil tested does not mean that a producer has to utilize this information. In that case, farm profits would be less since the farmer would pay the cost of testing. Furthermore, the potential of soil testing as a policy to improve groundwater quality is weakened if test information is not utilized. These issues are addressed below.

Implications and Conclusions

The primary purpose of this investigation was to assess the potential benefits of soil testing on ambient groundwater quality. Simulation results indicate that soil testing can improve groundwater quality beneath the study region by 2–6 ppm (2.5 ppm on average). While other studies have shown soil testing to improve farm income, and perhaps soil water quality (which serves as a proxy for groundwater quality), this study directly links changes in nitrogen input as a result of soil testing to changes in groundwater quality. The analysis thus addresses an important policy question of whether soil testing can reduce groundwater nitrate concentration sufficiently to eliminate the need for direct regulation of this form of agricultural nonpoint pollution.

The answer to this question, at least in our study region, is no. While model results indicate that soil testing all fields reduces high predicted groundwater nitrate levels within a soil zone and across the region, the reduction is not sufficient to meet the Oregon state groundwater quality target (7 ppm). Further, predicted levels for the high groundwater nitrate concentration are significantly less than observed levels in the base case. With soil testing, the regional mean groundwater nitrate concentration is in compliance, but specific zones are in violation. Generally, these results are not sensitive to the chosen level of residual soil nitrogen. The exception is the case where the producer ignores residual soil nitrogen (scenario 1, table 4). Under this scenario, groundwater quality is significantly reduced.

The second purpose of this analysis was to assess the impact of soil testing on farm income. As found in previous research, soil nitrogen testing improved per acre return. However, unlike previous research, soil testing also increased nitrogen applications. The improvement in per acre return is the result of increased revenue from increased yields (particularly in wheat), which exceed the cost of the additional fertilizer and the soil test. However, the improvement in per acre returns shown here is more modest than in earlier studies ($5 to $49, for an average of $17—rather than $20 to $50 per acre found in previous work). Note, however, that the crops, soils, and climate of the study region are very different from those of other studies which focus primarily on corn in the Corn Belt region.

This analysis assumes all fields will be soil tested when, in fact, soil testing in the region is voluntary. While identified as a best management practice to improve groundwater quality, in practice, it is left to the producer to soil test fields and, if tested, to utilize that information. Hence, actual improvements in groundwater quality are expected to be less (and the demand for regulation greater) because not all producers will test their soils. In fact, model results show that soil testing only improves regional average per acre return $5 over a strategy of ignoring residual soil nitrogen levels. Onions are a high-value crop, and yield is sensitive to climatic factors and nutrient availability. In this case, a producer would have to demonstrate a great deal of confidence in soil test results. Soil testing will have a greater impact on net returns to less valuable crops where there is less yield risk, but it is still unreasonable to expect all wheat fields to be tested.

Soil testing, while not solving the groundwater quality problem in the region, is a potential win-win alternative; it can improve groundwater quality and increase farm profits. Extension education, technical assistance, and cost sharing are all policy tools that promote voluntary adaption. There is evidence, however, that educational programs need to be accompanied with a regulatory program to ensure improvements in groundwater quality (Bosch, Cook, and Fuglie). While regulation may be necessary to meet the desired quality goal for the study region, alternative technologies and production practices need to be evaluated (particularly changes in irrigation application rates and methods). In fact, changes in irrigation technology may do more for improving groundwater quality than changes in nitrogen application rate or technology (Larson, Helfand, and House).

The integrated assessment framework developed in this investigation is a comprehensive representation of a complex, site-specific 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 this study apply to hydrological regions with similar soil characteristics and shallow aquifers that discharge to streams or rivers. Further extensions of this type of analysis include an accounting for an increase in the plateau yield as a result of increased soil testing (due to precision farming) and the addition of technology substitution. Taking advantage of soil test information may require adaption of new nitrogen application and irrigation technologies, which could improve returns to farmers and further reduce groundwater pollution.

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