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Dynamic Optimization of Nitrogen Use in Agriculture

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Abstract

Agricultural production is highly dependent on inorganic substances including fertilizers. High-yielding crop varieties, such as corn, require large amounts of primary nutrients including nitrogen, phosphorus and potassium. Farmers often add a surplus of nutrients to crops to maximize yields. Utilization of primary nutrients has increased by more than 300% while that of nitrogen alone has increased by more than 600% between 1960 and 2007 (USDA, 2009). From 1964 to 2007, the use of nitrogen in the corn sector alone increased from 1,623,000 to 5,714,000 nutrient tons (USDA, 2009).

While increasing production, increased fertilizer use can potentially create negative externalities in the form of nitrate-nitrogen contamination in groundwater. Groundwater is the source of drinking water for about half the total U.S. population and nearly all of the rural population, and it provides over 50 billion gallons per day for agricultural needs (USGS, 2009). In the U.S. the main source of nitrate pollution in the groundwater results from the actions of farmers through the use of fertilizers and other chemicals (Haller, et al. 2009). Nitrogen-nitrate contamination can have adverse human affects including methemoglobinemia or blue-baby syndrome (Majumdar, 2003).

The potential for nitrate contamination in corn production is especially problematic as corn alone accounts for over 90% of feed grains produced in the U.S. (USDA, 2009). The USDA estimates that approximately 80 million acres of land is planted to corn, with the majority in the Heartland region (the Midwest) of the U.S. (2009). The Heartland region is primarily rural and much of the population there derives its drinking water from groundwater. Therefore, the potential for groundwater contamination is greatly increased in this region.

Introduction

Agricultural production has been highly dependent on inorganic substances specifically fertilizers. Farmers resort to high-yielding crop varieties which require high amounts of primary nutrients namely nitrogen, phosphorus and potassium in order to generate higher returns. Utilization of primary nutrients has increased by more than 300% while that of nitrogen alone has increased by more than 600% between 1960 and 2007 (ERS). While having good effects on production, increased fertilizer use creates negative externalities for the environment. Nitrate-nitrogen (NO_3-N) pollution, which is a form of groundwater contamination, has been a serious environmental concern. Although such contamination may result from several sources including storage tanks, septic systems, hazardous waste sites, landfills, and the widespread use of road salts, the main source of nitrate pollution in the groundwater results from the actions of farmers through the use of fertilizers, and other chemicals (Haller, McCarthy, O'Brien, Riehle, and Stuhldreher).

Corn production is one of the agricultural crops that make use of nitrogen the most. From 1964 to 2007, the corn sector use of nitrogen increased from 1,623,000 to 5,714,000 nutrient tons (ERS). In Kentucky alone, which is one of the major corn growing states, 152,320 thousand bushels of corn grain was produced in 2008 (USDA-NASS). A big amount of corn production implies intensive us of nitrogen thus higher possibilities of nitrate-nitrogen groundwater contamination. Currently, there are 2746 sites with known or suspected groundwater contamination in Kentucky (GWPC). Particularly, nitrate incidence in groundwater is widespread with 9.7 percent of hand-dug wells and 1.1 percent of wells greater than 150 feet deep exceeded the maximum contaminant level (MCL) of 10 mg/L for nitrate.

Groundwater is the main source of drinking water in the United States, throughout Kentucky, 900,000 people use groundwater supplies, including approximately 500,000 supplied through public utilities and at least 400,000 using private wells or springs (Conrad, Carey, Webb, Dinger and McCourt). The high dependence on groundwater causes severe concerns on its increasing contamination due to expected adverse human effects. Hepatitis, dysentery, poisoning and cancer are some of the diseases that could be caused by contaminated water. Aside from humans, there are also negative effects on the wildlife health and the environment.

This study looks at the prevention of nitrate contamination. The goal of this study is to determine an optimal level of nitrogen use for corn when the groundwater externality from nitrogen uses is internalized at the standard (10 mg/l) over time. A dynamic optimization approach is utilized by specifying the corn response function and nitrate contamination levels. Data from the top ten corn producing counties in Kentucky were used. To bring the nitrate concentration in the groundwater to the standard over time, an optimal policy rule was derived where the current nitrogen application rate for each county was based.

Analytical Framework

The development of the model using the corn response and nitrate contamination levels and dynamic optimization of nitrogen use are extended in the following section.

Corn Response Function

The most commonly used agronomic response function is the quadratic function which is employed in this analysis. The algebraic formulation is:

$$Y_i = \beta_0 + \beta_1 N_i + \beta_2 N_i^2 + \varepsilon_i \tag{1}$$

where Y_i is corn yield (bushels), N_i is applied nitrogen (bushels), β_j (j = 1,2) are the parameters to be estimated, and ε_i are the stochastic errors.

The restriction of nonzero elasticity of substitution ($\sigma \neq 0$), the diminishing marginal productivity and the input substitution for all N_i >0 are imposed with the use of quadratic form. That is for β_1 >0 and β_2 < 0, yield decreases as N_i and P_i levels become large holding all other factors constant.

Nitrate Contamination and Nitrogen Application Vector

Presence of nitrate pollutants in the subsurface zone of the soil profile is mainly determined by the availability of nitrogen at the surface level. Natural events, such as rainfall, soil characteristics, and others, and human factors (farming activities, i.e. fertilizer applications, tillage practices, etc.) influence the rate and extent of movement of nitrogen to the subsurface. The stock of pollution in the aquifer, on the other hand is established by the increase in the contamination level from nitrate pollutants coming into the subsurface zone and reduction in pollution through denitrification (loss or removal of nitrogen or nitrogen compounds).

The stock of contamination (the state variable)

$$C_A \in \{C_0, C_1, C_2, ..., C_t\} \tag{2}$$

is the contamination level at the aquifer of county *A* at time *t*, (C_A).

The amount of nitrogen application (action variable)

$$N_A \in \{N_0, N_1, N_2, ..., N_t\} \tag{3}$$

is the amount of nitrogen applied in a given county *A* at time *t*, (N_A). Note that nitrogen application is the major factor responsible for accelerating the contamination level; therefore, the most effective way to decrease contamination is to reduce the level of nitrogen use.

Dynamic Optimization of Nitrogen Use

Due to the two dynamic processes (nitrogen application and denitrification), the stock of nitrate accumulates or degrades over time. Data, however, show that the rate of accumulation far exceeds the rate of natural degradation. The net effect of this process have some important economic tradeoffs between present costs of revenue foregone and the future benefits of preventing further accumulation of nitrate in groundwater. Lowering the use of nitrogen will decrease farm profits (present costs) however it will reduce nitrate build-up over time in groundwater (future benefits). Considering both current and future aspects of this conflict, a dynamic approach in solving the problem is employed to formulate the regulation for optimum control of pollution.

The state transition function is given by

$$G(C_A, N_A) = C_A + N_A \tag{4}$$

For a representative farm, a net social benefit function or reward function (private net benefit minus social cost of contamination) from the use of nitrogen in crop production and the associated contamination costs to society can be defined as

$$W(N_t, C_t) \tag{5}$$

Dynamic optimization of the present value of net social benefit in the framework of a discrete space, discrete time optimal control model may be stated using the Bellman equation as

$$V(C_A) = \max_{N_A}\{W(N_t, C_t) + \delta V(C_A - N_A\} \tag{6}$$

In order to develop solution algorithms, the following vector notation and operations are defined. Assume that the contamination levels $C_A = \{1,2, \ldots, p\}$ and nitrogen applications $N_A = \{1,2, \ldots, q\}$are indexed by the first p and q integers, respectively. Let $\upsilon \in \mathbf{R}^p$ denote an arbitrary value vector, then υ_i is the value in contamination level (state) i and let $N_A \in \mathbf{N}^p$ denote an arbitrary policy vector, then $N_{A,i}$ is the nitrogen application (action) for a particular contamination level i.

In addition, for each policy $N_A \in \mathbf{N}^p$, let $W(N_A) \in \mathbf{R}^p$ denote the p-vector of net social benefits earned in each contamination level when one follows the given policy. $W_i(N_A)$ gives the net social benefit when the contamination level is i, given nitrogen application $N_{A,i}$ is taken.

Lastly, let $P(N_A) \in \mathbf{R}^{p \times p}$ denote the p x p contamination level transition probabilities when one follows the given policy, $P_{ij}(N_A)$ is the probability of jump from contamination level i to j, given than nitrogen $N_{A,i}$ is applied.

The policy iteration algorithm is used to derive a solution. This algorithm applies Newton's method to the Bellman equation of discrete time discrete space decision model. The Bellman equation for the infinite horizon model may be concisely expressed as a vector fixed-point equation

$$
\begin{aligned}
\upsilon &= \max_{N_A}\{W(N_A) + \delta P(N_A)\upsilon\} \\
\upsilon &- \max_{N_A}\{W(N_A) + \delta P(N_A)\upsilon\} = 0
\end{aligned}
\tag{7}
$$

it may alternatively be stated as a rootfinding problem and solved using Newton's method. Using the Envelope Theorem, the first-order condition with respect to υ is $I - \delta P(N_A)$, where N_A is optimal for the maximization problem. It follows that the Newton iteration rule is

$$\upsilon \leftarrow \upsilon - [I - \delta P(N_A)]^{-1}[W(N_A) - \delta P(N_A)\upsilon] \tag{8}$$

where P and W are evaluated at the optimal N_A. Equation (8) can be rewritten as (9),

$$\upsilon \leftarrow [I - \delta P(N_A)]^{-1} W(N_A) \tag{9}$$

At the initialization stage, the net social benefit W, transition probabilities P, discount factor δ, and an initial guess for υ are specified. For policy iteration, using the starting value υ, update the policy N_A and then update the value υ

$$N_A \leftarrow \arg\max_{N_A}\{W(N_A) + \delta P(N_A)\upsilon\} \tag{10}$$

$$\upsilon \leftarrow [I - \delta P(N_A)]^{-1} W(N_A) \tag{11}$$

If the change in υ is equal to zero ($\Delta\upsilon=0$), the policy iteration should be stopped otherwise revisit the policy iteration stage.

Data Collection

The data for this study was obtained from several sources. The county-level nutrient inputs were collected from a dataset compiled by Ruddy, Lorenz, and Mueller (2006) with the U.S. Geological Survey. The data contains estimates for county-level nutrient inputs from 1982-2001. The state average fertilizer prices were obtained from the Economic Research Service within the U.S. Department of Agriculture (2009). The average prices and yields of corn (per bushel) were obtained from the National Agricultural Statistics Service also with the U.S. Department of Agriculture (2009). The groundwater contamination data were obtained from the groundwater-quality dataset within the Kentucky Geological Survey (2009). The Kentucky groundwater-quality dataset collects thousands of samples of groundwater quality across the state including private and public wells, springs, and aquifers. The data was averaged at the county level to get an estimate for county-level nitrate-nitrogen contamination.

Due to data limitations with the county-level nutrient inputs the estimates could only collected per annum for 1987-2001 yielding 15 observations. These estimates therefore form the baseline for the sample within the study. Due to data limitations this study was limited to the top ten counties for corn production within the state of Kentucky (specifically, Christian, Daviess, Graves, Henderson, Hickman, Logan, McLean, Todd, Union, and Webster Counties).

Empirical Model

We define a net social benefit function as $[W(N_t,C_t)]$ of the following type for the empirical analysis:

$$W(N_t, C_t) = P_{yt}(\beta_0 + \beta_1 N_t + \beta_2 N_t^2) - P_{nt} N_t - \theta C_t^2 \tag{12}$$

where P_{yt} average price of corn (per bushel) in the State of Kentucky at time t. Nitrogen inputs represent the action or control variables while the amount of nitrate concentration represents the state variable. N_t in Eq. (12) is the amount of nitrogen used (per bushel) at the county level at time t. P_{nt} is the average U.S. price of nitrogen at time t. θC_t^2 is the cost of contaminated groundwater to society—as Yadav (1997) we assume that it is proportional to the square of the nitrate contamination. Therefore, the first two terms on the right hand side (RHS) of Eq. (1) represent the private net revenue from the use of nitrogen. The implied optimization problem, in the framework of a discrete space, discrete time model, can be stated mathematically as

$$V_t(C_t) = \max_{N\in\{0,1,2,\ldots,\bar{N}\}}\{ P_{yt}(\beta_0 + \beta_1 N_t + \beta_2 N_t^2) - P_{nt}N_t - \theta C_t^2 + \delta V_{t+1} g(C_t, N_t)\} \qquad (13)$$

where δ is the discount rate. We define Eq. (2) as an infinite horizon problem. $g(C_t, N_t)$ is the deterministic state transition function defined as,

$$g(C_t, N_t) = C_{t+1} = \eta N_t - \phi C_t \qquad (14)$$

given $C_0=\bar{C}$. Where again, η represents a scaling factor of the effect of current nitrogen usage and φ represents the rate of degradation of the nitrate-nitrogen concentration (C_t) between the current and the following period. This equation explains how the nitrate-nitrogen (N_t) contamination in the groundwater is a function of the surface application of nitrogen and the denitrification of the existing nitrate concentration in the groundwater aquifer (C_t). Note that the specification of the deterministic transition function is consistent with the functions in previous studies such as Yadav (1997) and Nkonya (1999).

The Bellman equation in Eq. (13) was solved using a policy iteration method for the infinite horizon model as discussed in the “Dynamic Optimization of Nitrogen Use” section.

Empirical Results

The corn response function is the first term in parentheses on the RHS of Eq. (13). It was estimated as fixed effect panel data set with robust standard errors so that we could control for heterogeneous effects between the data sets. The data was examined to determine if there is a unit root within the series; i.e., if the series is non-stationary. The unit root hypothesis was rejected in favor of stationarity. The estimates for the fixed effects regression are listed in Table 1 with the standard error listed in parentheses below the estimates. Both signs are consistent with past studies of corn response function—i.e., diminishing marginal returns of nutrient inputs.

Table 1. Corn Yield Functions

$$Y = 42.50 + 0.76N - 0.001N^2$$
(26.87) (0.34) (0.00010)

Adjusted $R^2 = 0.102$ Sample Size = 150
$F(2,9) = 8.52$ Prob > F = 0.0084

The descriptive statistics for each county are listed below in Tables 2-4. The data for the corn yields and nitrogen inputs are fairly similar across counties and seem consistent. The statistics for nitrate concentrations show that four of the counties (Christian, Daviess, Hickman, and Union) have concentrations levels on average that are close to or above the EPA's standard for nitrate contamination.

Table 2. Descriptive Statistics of Corn Yield Per Bushel per County from 1987-2001

Corn Yield (bu)					
	Christian	**Daviess**	**Graves**	**Henderson**	**Hickman**
Mean	118.80	120.87	113.53	117.80	119.07
Standard Error	6.57	5.07	4.94	4.93	4.68
Median	118.00	121.00	114.00	114.00	121.00
Mode	106.00	145.00	114.00	128.00	130.00
Standard Deviation	25.46	19.62	19.14	19.11	18.11
Corn Yield (bu)					
	Logan	**McLean**	**Todd**	**Union**	**Webster**
Mean	120.00	121.87	118.67	129.27	119.87
Standard Error	7.63	5.10	7.12	4.66	4.54
Median	122.00	120.00	126.00	130.00	118.00
Mode	122.00	#N/A	#N/A	119.00	141.00
Standard Deviation	29.57	19.76	27.58	18.04	17.60

Table 3. Descriptive Statistics of Nitrogen Use Per Bushel per County from 1987-2001

Nitrogen Use (bu)					
	Christian	**Daviess**	**Graves**	**Henderson**	**Hickman**
Mean	193.75	190.58	152.09	132.35	68.96
Standard Error	8.56	5.15	5.29	5.39	3.14
Median	193.72	190.84	151.02	139.01	68.03
Mode	#N/A	#N/A	#N/A	#N/A	#N/A
Standard Deviation	33.15	19.94	20.48	20.88	18.11
Nitrogen Use (bu)					
	Logan	**McLean**	**Todd**	**Union**	**Webster**
Mean	168.02	94.52	122.61	136.05	82.97
Standard Error	3.48	1.74	4.82	3.69	1.25
Median	172.80	94.77	120.36	131.20	83.69
Mode	#N/A	#N/A	#N/A	#N/A	#N/A
Standard Deviation	13.49	6.75	18.67	14.28	4.83

Table 4. Descriptive Statistics of Nitrate-Nitrogen Concentration per County from 1987-2001

$N0_3$-N(mg/L)					
	Christian	**Daviess**	**Graves**	**Henderson**	**Hickman**
Mean	9.59	10.88	8.31	7.66	9.66
Standard Error	0.63	1.83	0.18	0.28	0.22
Median	7.33	9.20	7.15	6.38	8.73
Mode	#N/A	#N/A	#N/A	#N/A	#N/A
Standard Deviation	2.35	7.10	0.70	1.03	0.84
$N0_3$-N(mg/L)					
	Logan	**McLean**	**Todd**	**Union**	**Webster**
Mean	8.49	7.07	6.44	10.06	7.03
Standard Error	0.31	0.33	0.50	0.48	0.01
Median	7.82	6.13	5.03	9.51	6.01
Mode	#N/A	#N/A	4.10	4.70	0.00
Standard Deviation	1.21	1.27	1.94	1.87	0.04

Due to the lack of experimental data, as in case of Yadav (1997) or Nkonya (1999), we had to assume values for the parameters in the nitrate contamination function listed in Eq. (14). Following Yadav (1997) we estimate the nitrate contamination function as follows,

$$g(C_t, N_t) = C_{t+1} = 0.16N_t - 0.32C_t \tag{15}$$

where 0.16 is the scaling parameter for the effect of the nitrogen input (i.e., a unit increase in the nitrogen applied increase nitrate concentration in the vadose zone by 16%) 0.32 represents the degradation rate of the nitrate-nitrogen concentration before the next treatment of nitrogen; in other words, approximately 32% of the nitrate concentration is lost through natural denitrification processes between nutrient applications.

The results for the dynamic optimization of nitrogen usage are listed in Table 5. The first column represents the static profit-maximizing amount of nitrogen application while the second column demonstrates the dynamic-maximizing amount. Due to the static nature of the profit-maximizing amounts, the farmers at the county level do not take consideration of the externality into account and so the amounts in the first column are often substantially higher the amounts in the second column.

Table 5. Nitrogen Recommendations under Static Profit-Maximization and Dynamic-Maximization with the Social Cost of NO_3-N Internalized

County	**Profit-Maximizing Levels of Nitrogen (N_π) use (bu)**	**Nitrogen Levels with Social Costs for NO_3-N Concentrations**	**Percentage Change in Nitrogen Levels**
Christian	244	192	21.31%
Daviess	223	189	15.25%
Graves	184	149	19.02%
Henderson	160	129	19.38%
Hickman	88	69	21.59%
Logan	184	165	10.33%
McLean	104	93	10.58%
Todd	137	117	14.60%
Union	162	135	16.67%
Webster	92	79	14.13%

Optimal Policy Rule

According to Conrad and Olson (1992), the optimal control policy is a linear function given by,

$$C_{t+1} = \omega + \Omega C_t \tag{16}$$

where ω is a stochastic term that we assume to be a normally distributed white noise term; in time series analysis this may be described as a random walk without a drift. Ω is a weighting term that is less than one so that the optimal policy reaches an equilibrium level. To better understand this we rewrite Eq. (16) using the lag operator L to indicate a one period lag as follows,

$$C_t = \omega + \Omega C_{t-1} \Rightarrow C_t - \Omega C_{t-1} = \omega \Rightarrow (1 - \Omega \mathrm{L})C_t = \omega \Rightarrow C_t = (1 - \Omega \mathrm{L})^{-1}\omega \tag{17}$$

$$\Rightarrow C_t = (1 + \Omega \mathrm{L} + \Omega \mathrm{L}^2 + \Omega \mathrm{L}^3 + \cdots)\omega$$

Therefore, $\Omega < 1$ so that the rate of nitrate concentration is slowing declining (at an infinite horizon) to its equilibrium level over time. If $\Omega > 1$ then the optimal control policy would continually grow over time (i.e., there would be permanent persistence in the series) and the concentration level would deviate from the equilibrium level through time. For the steady-state nitrate concentration level of 10 mg/l in the groundwater (as recommended by the U.S. EPA) a numeric value of ω (say $\bar{\varepsilon}$) can be determined from Eq. (16) above given the available data. Specifically, $\bar{\varepsilon}$ was obtained by regressing the nitrate concentration level on its own lag and then we obtained the estimated residuals; then we took the average of the estimated residuals to estimate $\bar{\varepsilon}$. Ω then is the coefficient on the lagged value of the concentration level in the nitrate concentration level. Finally, the optimal nitrogen application rate can be obtained by substituting the nitrate contamination function (the deterministic transition function) into Eq. (16) and then solving for N_t as a function of C_t,

$$0.16N_t - 0.32C_t = \bar{\varepsilon} + \Omega C_t \Rightarrow N_t = \frac{1}{0.16}[\bar{\varepsilon} + C_t(1.04)] \tag{18}$$

Based upon Eq. (18) we derived the optimal policy rules of nitrogen application in each county. The results are listed in Table 6. We collected nitrate concentration levels in each county starting one period prior (1986) to account for initial values of the concentrations.

To clarify the relationship between the equilibrium level of nitrogen and nitrate concentration we plot a graph of the optimal trajectories in Figure 1 below, where N^* and C^* are the equilibrium levels of nitrogen input and the nitrate concentration level respectively.

Table 6. Optimal Policy Rules for Nitrogen Applications in Each County

County	Optimal Policy Rule	
Christian	$N_t = 427.62 - 6.42C_t$	if $N_t < N_\pi$
	$N_t = N_\pi$	if $N_t > N_\pi$
Daviess	$N_t = 412.37 - 6.26C_t$	if $N_t < N_\pi$
	$N_t = N_\pi$	if $N_t > N_\pi$
Graves	$N_t = 434.84 - 6.57C_t$	if $N_t < N_\pi$
	$N_t = N_\pi$	if $N_t > N_\pi$
Henderson	$N_t = 456.62 - 6.28C_t$	if $N_t < N_\pi$
	$N_t = N_\pi$	if $N_t > N_\pi$
Hickman	$N_t = 437.27 - 6.52C_t$	if $N_t < N_\pi$
	$N_t = N_\pi$	if $N_t > N_\pi$
Logan	$N_t = 421.75 - 6.13C_t$	if $N_t < N_\pi$
	$N_t = N_\pi$	if $N_t > N_\pi$
McLean	$N_t = 436.87 - 6.62C_t$	if $N_t < N_\pi$
	$N_t = N_\pi$	if $N_t > N_\pi$
Todd	$N_t = 426.01 - 6.19C_t$	if $N_t < N_\pi$
	$N_t = N_\pi$	if $N_t > N_\pi$
Union	$N_t = 427.34 - 6.35C_t$	if $N_t < N_\pi$
	$N_t = N_\pi$	if $N_t > N_\pi$
Webster	$N_t = 434.87 - 6.47C_t$	if $N_t < N_\pi$
	$N_t = N_\pi$	if $N_t > N_\pi$

Concluding Remarks

Our analysis shows that if farmers (in the top ten corn-producing counties level in the State of Kentucky) internalize the costs of nitrogen-nitrate concentrations, the use of nitrogen could decrease by as much as 16.28% on average which translates roughly to a 9% decrease in the concentration levels of nitrogen-nitrate. Although 9% may seem like a small number, this slight change would be enough to bring Daviess and Union counties (recall from Table 4 the concentration levels on average were 10.88 and 10.08 milligrams per liter respectively) within the EPA's recommended levels of nitrate-nitrogen concentration (10 mg/L) in the groundwater. This decrease could also help Christian, Graves, Hickman, and Logan counties help maintain their current concentration levels as they are each getting dangerously close to exceeding the EPA recommended levels.

This study was limited by only having the data available at the county level as opposed to having onsite data available. By aggregating to the county level we had to make several simplifying assumptions including farmers' nitrogen application rates are roughly the same on average, corn yields are roughly uniform at the county level, and the nitrogen-nitrate concentration levels were caused mostly by the nitrogen application of farmers. The last assumption is not too problematic given that the groundwater samples were taken from rural areas designated for agricultural use. The first two assumptions are a little more problematic; however our analysis shows that if farmers at the county level could be educated (perhaps through a university county extension office) about the potential hazards of nitrogen-nitrate contamination it could have considerable affects on their fertilizer/nutrient application practices. The county-level average concentration levels could also alert State or federal government regulatory agencies as to potential nitrogen-nitrate contamination hazards that may arise.

Our analysis could have benefited greatly by having onsite readings of corn production, appetizer/nutrient application rates, and nitrogen-nitrate concentrations level. Such data sources are incredibly difficult to obtain unfortunately as farmers face fears of regulatory repercussions should they provide such information to the public. Future research could benefit by obtaining such data so that accurate readings of crop yield, fertilizer/nutrient use, and onsite nutrient concentrate levels in groundwater.

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Appendix

Figure 1. Characterization of isoclines, and the saddle path for the stable equilibrium at (N^*,C^*)