Dynamic Optimization of Nitrogen Use in Agriculture

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Problem

Agricultural producers often seek to maximize crop yields by increasing nitrogen inputs. If nitorgen application are too excessive, however, then harmful nitrate concentrations can leach into groundwater. High concentrations of nitrate are harmful to humans and the ecosystem. For example, excessive concentrations of nitrate in drinking water can cause Blue Baby Syndrome in infants less than 6 months of age.

Objectives

The goal of this study is to determine an optimal level of nitrogen use for field crop production in the state of Kentucky when the costs of groundwater contamination from nitrogen use is internalized by the producer. Specifically, we looked at four counties in Southwestern Kentuky — Christain, Logan, Todd, and Trigg Counties. With this optimization strategy the producer seeks to maximize crop yields through nitrogen applications, however, the social costs of groundwater contamination induces the producer to reduce the nitrogen inputs.

Model and Method

We utilize a discrete time, discrete state dynamic model framework. The optimization problem is,

$$V_t(C_t) = \max \{P_{yt}(\beta_0 + \beta_1 N_t + \beta_2 N_t^2) - P_{nt}N_t - \vartheta C_t^2 + \delta V_{t+1} \bullet g(C_t, N_t, \varepsilon_t)\} \quad (1)$$

where the first three terms define the net social benefit function and the last term is the discounted deterministic state transition function. P_{yt} denotes the average price of corn in the state of Kentucky at time *t*. Nitrogen inputs, N_t, represent the action or control variables while the nitrate concentration, C_t, represents the state variable. The average U.S. price of nitrogen at time *t* is given by P_{nt}. ϑC_t^2 denotes the cost of contaminated groundwater to society. δ denotes the discount rate and ε is an exogenous random shock that is unknown in period *t-1*.

The net social benefit function specifies a quadratic agronomic response function which defines the relationship between fertilizer inputs, N_t, and crop yields, Y_t, as follows

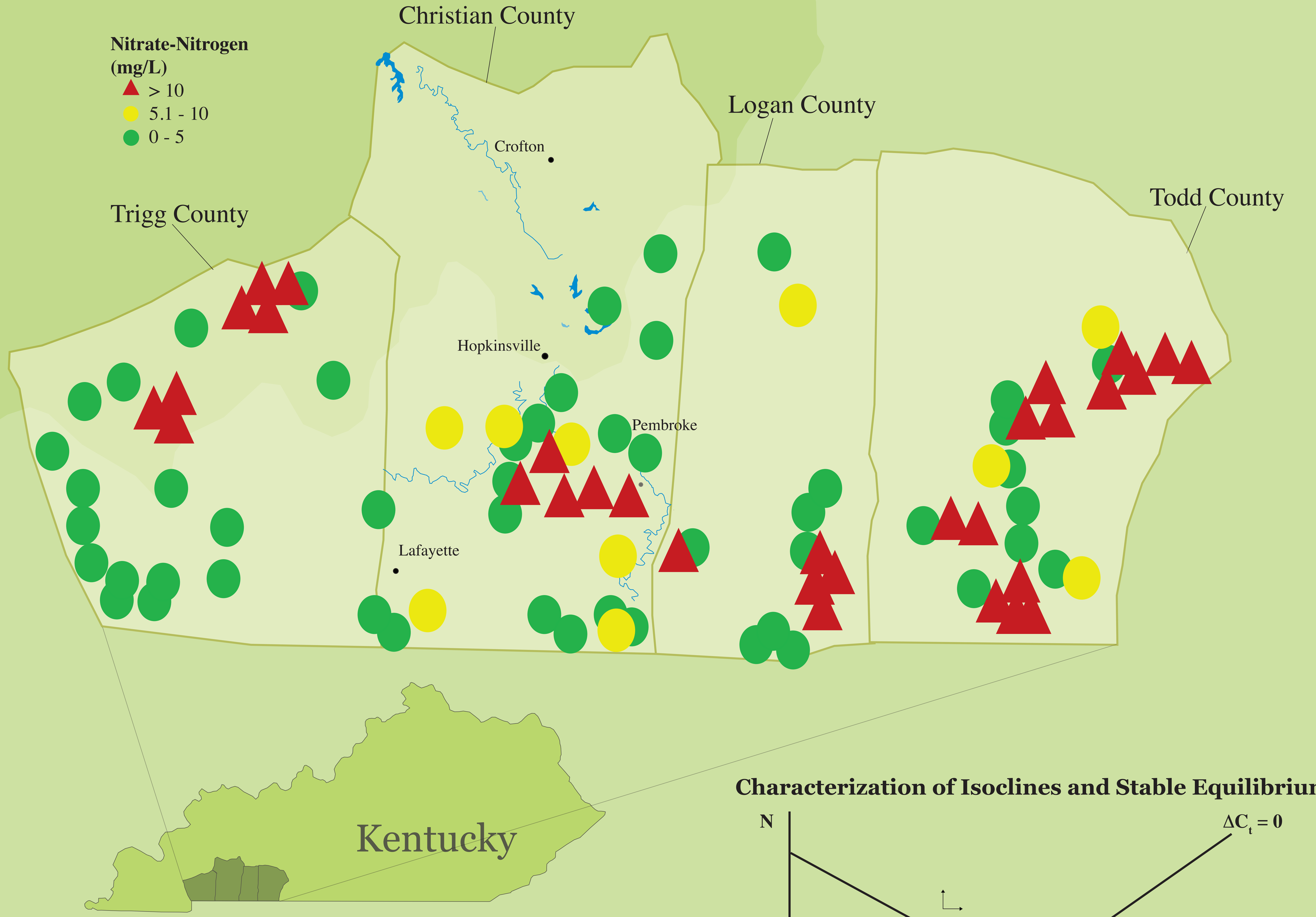
$$Y_t = \beta_0 + \beta_1 N_t + \beta_2 N_t^2 + \varepsilon_t$$

We consider corn specifically for the crop yield function. $g(C_t,N_t)$ is the deterministic state transition function which we define as,

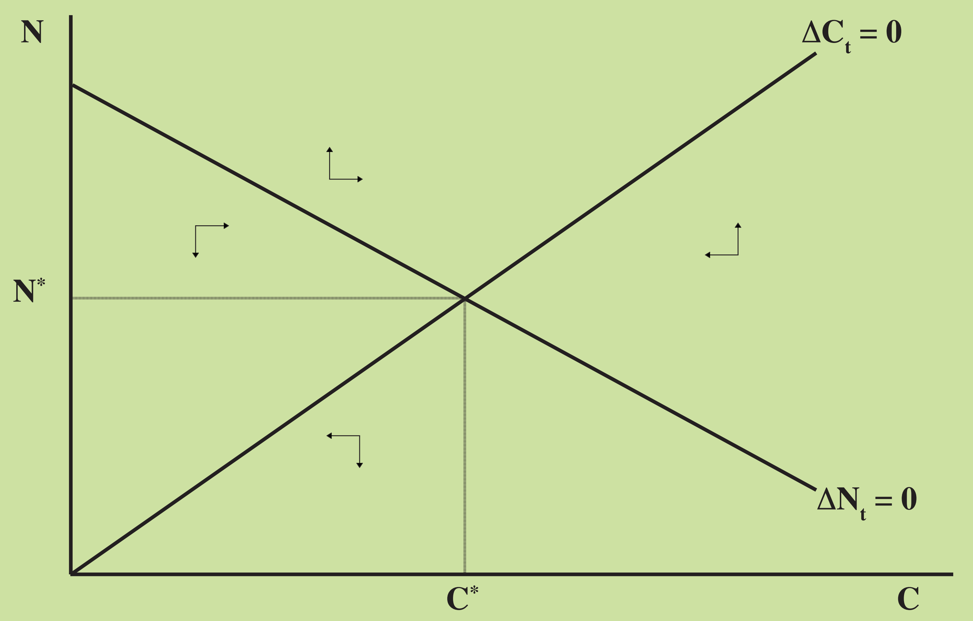
$$g(C_t,N_t) = C_{t+1} = \eta Nt - \phi Ct \quad (2)$$

where η denotes a scaling factor of the effect of current nitrogen usage and ϕ represents the rate of degradation of the nitrate-nitrogen concentration between the current and the following period. Intuitively, equation (2) explains how nitrate-nitrogen contamination in groundwater is a function of the surface application of nitrogen and the natural process of denitrification within the groundwater aquifer.

Nitrate-Nitrogen Concentrations in Wells and Springs



Characterization of Isoclines and Stable Equilibrium



Empirical Results

The agronomic response function was estimated by a fixed-effects panel with robust standard errors. The results from the fixed effects regression are listed in Table 1 with the standard errors listed in parentheses below the estimates

Table 1. Agrinomic Response Function

$$Y = 10{,}093.92 + 40N - 0.0186727N^2 - 354.2145\,drought$$
(3,322.2) (27.24) (0.0053) (301.34)

Adjusted R^2 = 0.0.0817   Sample Size = 150
F(9,137) = 0.82   Prob > F = 00.5984

The results for the dynamic optimization of nitrogen inputs are listed in Table 2. 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 profit-maximizing amounts, the producers do not consider the externality of potential nitrate contamination, so the amounts in the first column are often substaintially higher than the second column.

Table 2. Nitrogen Recommendations under Static Profit-Maximization and Dynamic Maximization with the Social Costs of $N0_3$-N

County	Profit-Maximizing Level of Nitrogen (lbs/Acre)	Average Nitrogen Levels with Social Costs of NO_3-N (lbs/Acre)	Percentage Change in Nitrogen Levels (%)
Christian	207.14	142.08	31.41
Logan	189.77	163.27	13.97
Todd	195.49	156.99	19.7
Trigg	256.51	232.03	9.54

Conclusions

Our analysis shows that if producers internalize the costs of nitrogen-nitrate contamination, the use of nitrogen could decrease by as much as 18.66% in Christian, Logan, Todd and Trigg Counties. This 19% decrease may seem inconsequential but it translates into a reduction of approximately 40 pounds of nitrogen per planted acre. This slight reduction would be enough to bring everyone of the red-designated wells into the EPA's recommended level of nitrate concentration (10 mg/L).

References

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