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An assessment of soil nitrogen testing considering the carry-over effect

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Abstract

In order to evaluate the economic and environmental consequences of soil nitrogen tests, this paper combines a dynamic fertilizer use decision model with a crop production model. The pre-side-dress soil N-test is evaluated for a hypothetical farmer growing corn at the ARS Sustainable Agriculture Demonstration Farm site in southern Maryland. For a farmer not currently using a soil N-test, adoption of this technology can lead to the enhancement of net farm income and the reduction in nitrogen loss to the environment. This will transpire only if the farmer is currently underestimating nitrogen carry-over by more than 25% or applying nitrogen fertilizer based solely on an expected plateau-yield goal.

1. Introduction

The application of nitrogen fertilizer on farms has been identified as a major contributor to the presence of nitrogen in groundwater and surface water in some areas in the United States. Nitrogen becomes a pollutant when excess nitrogen enters the groundwater and surface water through runoff and leaching. Nitrogen leached into groundwater can threaten the safety of drinking water. A national well survey by the Environmental Protection Agency indicated that many drinking water wells in several states have nitrate levels above the recommended maximum contaminant level (US Environmental Protection Agency, 1990). Similarly, nitrogen runoff can cause eutrophication of streams, rivers, and lakes thereby damaging ecosystems ad biodiversity (National Research Council, 1989).

Soil nitrogen testing (N-testing) has been promoted as an important method to help in reducing nonpoint source pollution (US Environmental Protection Agency, 1993). It provides information to assist farmers in improving the application and timing of nitrogen fertilizer. It reveals the level of nitrogen in the soil profile enabling a farmer to determine whether and how much additional nitrogen fertilizer is needed for crops, to avoid excess use of nitrogen fertilizer, and consequently

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[1] The views expressed are those of the authors and do not necessarily represent the views of the US Department of Agriculture.

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to reduce nitrogen fertilizer costs (private costs) as well as nitrogen losses through leaching and runoff (social costs).

There are two types of soil N-testing: pre-plant nitrogen tests (PPNT) and pre-side-dress nitrogen tests (PSNT). PPNT is conducted before planting while PSNT is conducted after planting and before side-dressing nitrogen fertilizer is applied. Because it is the most common and extensively used, just the use of PSNT will be considered here.

The effectiveness of soil N-testing in predicting nitrogen fertilizer needs varies by region because of differences in site-specific characteristics such as precipitation, evapo-transpiration, soil type and texture, depth of the root zone and nitrogen carry-over from previous years. Generally, soil N-testing is reported to be effective in the Upper Midwest, the Northeast, and Wisconsin. It also is most effective when applied on fields following a dry year and on those fields with manure applications in the previous year (Bock et al., 1992).

Interest in soil N-testing has grown in recent years beyond its traditional role in improving farming profitability to include its potential role in reducing offsite water pollution. It has been shown that, in certain situations, soil N-testing can help a farmer enhance net farm income while reducing nitrogen fertilizer use. For example, Shortle et al. (1993) show that soil N-testing may reduce nitrogen fertilizer use and decrease excess nitrogen available for potential leaching and runoff. They also demonstrate, however, the opposite effects are conceptually possible. They conclude that the potential economic and environmental gains from the adoption of soil N-testing are empirical issues. Using results from a Pennsylvania farm survey, they find positive economic and environmental benefits associated with the use of soil N-testing. Babcock shows that temporal uncertainty regarding nitrogen available at the time of fertilizer application can affect the optimal nitrogen fertilizer application rate. Babcock and Blackmer (1992) conclude that use of soil N-testing to remove the temporal uncertainty of nitrate concentration in the soil can reduce average nitrogen fertilizer application rates by up to 38% and can increase net farm income by up to $22 per acre per year in Iowa. Bosch et al. (1994) find that the effects of soil N-testing on nitrogen fertilizer use are influenced by farmers' attitudes toward risk and by the assumptions regarding the nature of the production function. They show that use of soil N-testing is likely to help risk-averse farmers reduce nitrogen fertilizer use. Analyzing survey data from Nebraska, Fuglie and Bosch (1995) conclude that the economic and environmental benefits of soil N-testing to farmers depend on the cropping history of the cropland (e.g., what crop was grown in prior years), soil characteristics, and whether manure is applied coincident with the nitrogen fertilizer.

While these and other previous economic analyses have been useful in understanding the soil N-testing decision, they have failed to consider the nitrogen carry-over effect. They uniformly assume that in the absence of soil N-testing, nitrogen fertilizer in excess of crop needs is lost from the cropland. Such an assumption may inflate the benefit of soil N-testing by suggesting that nitrogen fertilizer application should be lower than might otherwise be the case. For example, in areas where the nitrate leaching problem is not severe, not all residual (unused) nitrogen will be lost. Instead, some of it will carry-over to the next crop year and can become an important source of nitrogen for the crops. Consequently, in this instance the amount of nitrogen fertilizer that should be optimally applied will be less than if all of the residual nitrogen had been lost.

Given these considerations, the objective of this study is to evaluate the economic and environmental benefits of soil N-testing when information about nitrogen in the soil and available for plant uptake is explicitly considered. The net economic (private) benefit of soil N-testing is the gain in net farm income associated with using soil N-testing to determine the requisite (optimal) application rate of nitrogen fertilizer. The net environmental (social) benefit of soil N-testing is the reduction in nitrogen loss to the environment as a consequence of the use of soil N-testing to reduce the nitrogen fertilizer application rate below what it would be in the absence of such a test. The realization of such benefits are influenced not only by site-specific variables but also by the farmer's current knowledge about best nutrient management practices. In the absence of soil N-testing, a farmer will employ a variety of alternative nitrogen management practices. For example, a farmer may systematically apply nitrogen fertilizer at a rate based on some assumed rate of nitrogen carry-over. This assumed rate can be incorrect. A farmer may use a maximum expected yield goal based on past observations to determine the nitrogen fertilizer application rate. A farmer may use past yield information to update the yield goal when determining the nitrogen fertilizer application rate. The economic and environmental benefits of soil N-testing can be estimated as a farmer switches from one of these practices to the practice of using the PSNT. Such an assessment will be carried out in what follows. Data from crops grown at the USDAs Agricultural Research Service Sustainable Agriculture Demonstration Farm in southern Maryland will be used in the assessment.

Since the economic and environmental benefits of soil N-testing are site-specific, the results from a field on which no soil N-testing is used must be compared with the results from the same field on which no soil N-testing is employed. The comparison will require the use of an economic model and a crop production process model. The economic model, which is developed in the next section, is a dynamic optimization model which determines the optimal nitrogen fertilizer application rate by including the nitrogen carry-over effect. The optimal nitrogen fertilizer application rate is used to provide a benchmark for the soil N-testing evaluation. The crop production process model is a stochastic crop growth model which simulates crop production as a function of carry-over nitrogen and weather variables such as daily precipitation and temperature. The crop production process model is used for two purposes: (1) to generate data for the estimation of a yield function and a carry-over function that are required for the empirical estimation of the optimal nitrogen fertilizer application rate, and (2) to simulate crop production under alternative nitrogen fertilizer management practices when carry-over nitrogen is present.

2. The dynamic economic optimization model

The economic consequences of adopting soil N-testing is measured by the magnitude of the present value of expected net farm income over a fixed time horizon. The model assumes that farmers maximize net farm income associated with nitrogen fertilizer use. The model provides a dynamic rule which then is used to determine a steady-state nitrogen fertilizer application rate and nitrogen loss to the environment. The steady-state solution of the model is used as the reference point (benchmark) for evaluating the consequences of the adoption of soil N-testing.

Taylor and Kennedy (TK) formulate a stochastic dynamic economic model considering the nitrogen carry-over effect. They assume that (1) there exists a stochastic yield function, $y_t = y_t(r_t,\delta_t)$, which is based on available nitrogen r_t and a random variable δ_t; (2) there exists a stochastic carry-over function $h_t = h_t(r_t,\mu_t)$, which is also based on available nitrogen r_t and a random variable μ_t; (3) there is independence between the fertilizer price and the nitrogen carry-over; and (4) there is agronomic equivalence between carry-over nitrogen and applied nitrogen. The TK stochastic dynamic model is formulated to solve the following problem. Maximize the present value of expected net farm income:

$$\max_{a_1 \ldots a_n} \quad \sum_{t=1}^{n} \alpha^{t=1} E(P_t^y y_t - p_t^f a_t), \tag{1}$$

$$\begin{aligned} \text{s.t.} \quad & r_t = x_t + a_t, \\ & x_{t+1} = h_t, \\ & a_t \geqslant 0 \\ & \text{with } x_1 \text{ given,} \end{aligned} \tag{2}$$

where: a_t is the application rate of nitrogen fertilizer in period t, p_t^y the price of the crop, y_t a stochastic yield function, p_t^f the price of nitrogen fertilizer in period t, α the time preference discount factor which is determined by $1/(1+\beta)$, where β is the interest rate, x_t the amount of nitrogen carried over to period t, h_t the stochastic nitrogen carry-over function, and r_t nitrogen available for plant uptake in period t.

Fixed costs are ignored because they do not affect the determination of the amount of nitrogen fertilizer to be applied. The TK stochastic dynamic economic model is clearly designed for a risk-neutral farmer who wants to determine the optimal nitrogen fertilizer application rate in order to maximize the present value of expected net farm income from producing a crop on a field. The fertilizer use decision is assumed to be independent of other input use decisions.

The problem described in Eqs. (1) and (2) has been solved by TK. Assuming that the expected price of fertilizer in period $t+1$ can be determined by the fertilizer price in period t, denoted as $E[p_{t+1}^f \mid p_t^f]$, and that the fertilizer price and the nitrogen carry-over are independent, they derive a deterministic rule for the optimal nitrogen fertilizer application rate. The TK rule is expressed as

$$E\left[p_t^y\right]\partial E[y_t]/\partial a_t = p_t^f - \alpha\partial E[h_t]/\partial a_t E[p_{t+1}^f \mid p_t^f]. \tag{3}$$

The rule equates the expected value of the marginal product of nitrogen fertilizer in period t to the nitrogen fertilizer price in period t less the discounted marginal value of nitrogen applied in the current period t to be carried over to the next period $t+1$. Thus, the solution can be obtained by solving a simple deterministic static certainty equivalence problem (Taylor, 1983).

One potential problem arises from the application of the TK rule. Improper specification of the carry-over function, $h_t(r_t, \mu_t)$, in Eq. (3) can lead to infeasible results. [2]

A proper specification of the nitrogen carry-over function must use a nitrogen mass balance framework. In such a setting, a nitrogen carry-over function can be specified as

$$h_t = v_t(r_t - \kappa y_t), \tag{4}$$

where $(r_t - \kappa y_t)$ is the amount of residual nitrogen available for plant uptake. That is, it is the difference between the total amount of nitrogen available for plant uptake, r_t, and nitrogen in the harvested crop removed from the field, κy_t, where κ is the amount of nitrogen in one unit of the harvested crop. The percentage of residual nitrogen to be carried over to the next period is

[2] Kennedy (1986) has pointed out that a major shortcoming of specifying the carry-over relationship solely as a function of r_t is the absence of any consideration of the significant effect of a harvested crop on the amount of nitrogen carried over to the next time period. A low crop yield in period t because of low rainfall, for example, can lead to low nitrogen uptake. This leaves more nitrogen than usual to be carried over to the next period, $t+1$. On the other hand, a high yield in period t because of favorable weather conditions can lead to high nitrogen uptake leaving less nitrogen than usual to be carried over to next period, $t+1$. Specification of a carry-over function without explicit consideration of the effect of nitrogen in the harvested crop can violate the nitrogen mass balance relationship and result in an infeasible solution. This problem can be corrected when specifying the nitrogen carry-over function by using the nitrogen mass balance principle which includes these effects (Meisinger et al., 1992).

given by the function, $v_t = v_t(r_t, \varepsilon_t)$. This is a stochastic function of r_t and a random variable ε_t. With this carry-over function and given an initial value for x_t, and with the assumption that v_t and the amount of residual nitrogen are independent, [3] the optimal fertilizer application rule becomes [4]

$$\alpha E[p_t^y]\partial E[y_t]/\partial a_t = p_t^f - \alpha\partial(E[v_t](r_t - \kappa E[y_t]))/\partial a_t E[p_{t+1}^f \mid p_t^f] \quad \text{for } t = 1, \ldots, n. \tag{5}$$

A profit-maximizing farmer can use this relationship to determine the optimal nitrogen fertilizer application rate, a_t^*, in period t. Knowing only the initial nitrogen level in the soil, x_t, the expected crop price at harvest time, p_t^y, the expected nitrogen fertilizer price in the next period $t+1$, p_{t+1}^f, which is based on the current (known) fertilizer price, p_t^f, the concave expected nitrogen carry-over rate function and expected yield function, an optimal value of nitrogen available for plant uptake, r_t^*, can be computed. The optimal nitrogen fertilizer application rate, a_t^*, is determined by subtracting the initial value x_t from r_t^*. Note that the optimal nitrogen fertilizer application rate in the current period t is not affected by either the amount of carry-over nitrogen in previous periods or the prices of nitrogen fertilizer and the crop in future periods. This rule is particularly useful for nutrient management when soil N-testing is used to determine the initial nitrogen level.

3. The steady-state solution for the dynamic economic optimization model

The optimal "steady-state" value of nitrogen available for plant uptake is a constant amount of nitrogen in the soil, r^*, that must be maintained at a specific time for plant uptake in order to maximize the net farm income (relationship (1)). It is determined by assuming that both expected prices of nitrogen fertilizer and the crop are constant and that the expected yield function and the expected nitrogen carry-over rate function are invariant over time (that is $y = y_t$ and $v = v_t$). Annual soil N-test will be needed to reveal the amount of carry-over nitrogen, x_t, for the determination of the annual amount of nitrogen to be added to maintain r^*. In the absence of a soil N-test, a farmer must exogenously determine the optimal steady-state nitrogen application rate a^*, and apply this rate annually to maximize the net farm income.

To keep the mathematics tractable, the optimal steady-state application rate will be determined from relationship (5) for just two time periods, $t = 1, 2$. In the first period, the optimal amount of nitrogen available for plant uptake, $r_1^*(= r^*)$, is obtained by the solving relationship (5) using the initial condition, x_1. Then, the optimal nitrogen fertilizer application rate, a_1^*, at period 1 is obtained by subtracting x_1 from r_1^*. The amount of residual nitrogen expected to be carried over from period 1 to period 2, $E[x_2]$, is $E[v(r^*)]\{r^* - \kappa E[y(r^*)]\}$, which is a constant. The expected steady-state level of nitrogen carried over, x^*, is equal to $E[x_2]$. By subtracting x^* form r^*, the steady-state optimal application rate, a^* is

$$a^* = r^* - E[v(r^*)]\{r^* - \kappa E[y(r^*)]\}. \tag{6}$$

Thus, corresponding to a given r^* and with a constant expected yield, $E[y(r^*)]$, and a constant expected carry-over rate of nitrogen, $E[v(r^*)]$, there is an optimal steady-state fertilizer application

[3] The percentage of residual nitrogen carried over to the next time period need not be a simple function of the level of residual nitrogen currently on the soil. It may more realistically be determined by soil characteristics and effective precipitation (Schaffer et al., 1990; Williams and Krissel, 1990). Therefore, the expected carry-over rate is more properly a function of the average of the annual carry-over rates over time. The relationship between $E[y_t]$ and $E[v_t]$ is discussed in a following section in the context of the estimation of these two functions.

[4] See Appendix A for the detailed derivation.

rate, a^*. [5] By applying this amount of nitrogen fertilizer annually, a farmer, in the absence of soil N-test, will maximize the present value of expected net farm income in the long run.

A farmer can use the steady-state solution to manage the application of nitrogen fertilizer in two ways – with or without a soil N-test – when faced with a stochastic yield function and a stochastic nitrogen carry-over rate function. With soil N-testing, the farmer can apply the additional amount of nitrogen fertilizer needed to maintain nitrogen at the optimal level, r^*. Without using a soil N-test, the farmer will annually apply nitrogen fertilizer at the optimal steady-state application, a^*. In this instance, the application rate will be constant since both the optimal amount of nitrogen available for plant uptake, r^*, and the nitrogen fertilizer carry-over rate, x_t, are constant over time. Theoretically, the farmer who uses the soil N-test will obtain the maximum present value of expected net farm income over the planning horizon. The farmer who does not use the soil N-test will have a smaller present value of expected net farm income than the one uses soil N-test. The reason is that the farmer who annually applies variable amounts of nitrogen fertilizer based on the results of a soil N-test can maintain the amount of nitrogen available for plant uptake at r^*. The farmer who does not use a soil N-test, however, and annually applies a constant amount of nitrogen fertilizer cannot maintain the amount of nitrogen available for plant uptake at r^* ever year. [6] Without the use of a soil N-test, the actual amount of nitrogen available for plant uptake will be larger than r^* in some years and smaller in other years, although the expected value of r is equal to r^*. Consequently, because of diminishing marginal returns of nitrogen fertilizer (Bosch et al., 1994), the farmer who does not use soil N-testing will realize ex post a smaller aggregate net farm income.

Next, the corresponding expected steady-state residual nitrogen, w^* (i.e., the amount of nitrogen fertilizer applied in excess of the amount of nitrogen removed with the harvested crop), can be calculated by the equation $w^* = a^* - \kappa E[y(r^*)]$. It can be shown that w^* is the expected amount of nitrogen loss at the steady state. As noted, for a specific field, there is an optimal value of r^* for given nitrogen fertilizer and crop prices. At the steady-state, the amount of residual nitrogen determines the amount of nitrogen loss. [7]

It is clear that the steady-state solution does not hold when unusual weather conditions such as drought occur and cause a crop failure. Under such a situation, soil N-testing must be used to detect excess nitrogen accumulation in the soil and help the farmer adjust the application rate of nitrogen fertilizer so as to maintain the amount of nitrogen available for plant uptake at r^*.

4. The crop production process model

In order to obtain the steady-state solution for the amount of nitrogen that must be available for plant uptake, r^*, the expected yield response (production) function, $E[y]$, and the expected

[5] Taylor proves the existence of a unique value of r^*. He states that "… it is determined only for the time period for which the optimal nitrogen fertilizer application is to be determined, rather than for an arbitrarily large number of time periods typically assumed to assure convergence of the decision rule as in the standard dynamic programming model".

[6] The difference in the nitrogen application rate between the situations when soil N-testing is used and when it is not used can be illustrated by a simple example: With soil N-test used, the farmer annually applies nitrogen fertilizer in the $a_t = r^* - x^* + \Lambda_t$, where x is the expected carry-over rate of nitrogen, and Λ_t is a the random error with zero mean and finite variance. The value of x^* can be observed when a soil N-test is used. Without a soil N-test, however, the farmer annually applies nitrogen fertilizer in the amount $a^* = r^* - x^{**}$, where $x^{**} = E(x_t)$. This latter term, $E(x_t)$, is constant over the planning horizon so that a^* is time invariant.

[7] The contention that the expected amount of nitrogen loss, ϕ, is equal to the expected amount of residual nitrogen, w^*, at the steady state can be demonstrated in a straightforward fashion. At the steady state, $x^* = E[v(r^*)]\ \{x^* + a^* - \kappa E[y(r^*)]\}$. Define expected residual nitrogen as $w^* = a^* - \kappa E[y(r^*)]$. Then, $x^* = E[v(r^*)](x^* + w^*)$, which can be expressed as $x^* = E[v(r^*)]/\{1 - E[v(r^*)]w^*\}$. Substitute x^* into the nitrogen loss equation $\phi = (1 - E[v(r^*)])(x^* + w^*)$. This gives $\phi = w^*$.

Table 1
Nitrogen mass balance

(i) Input – (FN_t + $NPRCP_t$ + $NFIX_t$)
(ii) Output – (YLN_t + $SSFN_t$ + $PRKN_t$ + DN_t + YNO_{3t} + $AVOL_t$)
(iii) Organic N change – (ORG N AC_{t+1} + ORG N ST_{t+1}) − (ORG N AC_t + ORG N ST_t) − YON_t
(iv) N available for plant uptake – ((Input + NO_{3t}) − Organic N change)
(v) Estimated $NO_{3(t+1)}$ – (Eq. (iv) – Eq. (ii))
(vi) N available for carry-over – (Eq. (iv) − YLN_t)

Definitions: FN – N fertilizer applied (kg/ha), NPRCP – N in precipitation (precipitation ×.008) (kg/ha), NFIX – N fixed by legumes (kg/ha), YLN – N in crop yield (kg/ha), YON – organic N loss in sediment (kg/ha), SSFN – mineral N loss in subsurface flow (kg/ha), PRKN – mineral N loss in percolate (kg/ha), DN – loss by denitrification (kg/ha), YNO_3 – NO_3 loss in surface runoff (kg/ha), AVOL – nitrogen volatilization (kg/ha), ORG N AC – organic N concentration in the active pool (kg/ha), ORG N ST – organic N concentration in the stable pool (kg/ha), NO_3 – nitrate concentration (kg/ha) in the soil profile.

nitrogen carry-over rate function, $E[v]$, for a specific field under a given nutrient management practice must be estimated. The Erosion Productivity Impact Calculator (EPIC) can provide the requisite data for the estimation of these two functions. The EPIC model is a comprehensive crop production process model developed by USDAs Agricultural Research Service (ARS) primarily to estimate soil erosion and its impact on soil productivity in the United States (Williams et al., 1990). [8] It has also evolved into an important tool to simulate degradation and movement of agricultural chemicals in the soil. The EPIC model is a stochastic crop production process model whereby crop growth and the fate of nitrogen, including carry-over nitrogen, are subject to the stochastic variation of daily weather. In EPIC model simulations, daily precipitation, temperature, and solar radiation are randomly generated from assumed probability distributions (Richardson and Nicks, 1990). As a consequence, annual crop yield and the nitrogen carry-over rate are stochastic functions. The crop growth component in the EPIC model generates data for the estimation of the stochastic yield response function. The yield response function must be empirically estimated since crop yields in the EPIC model are determined by a harvest index and above-ground biomass and are indirectly linked to the available nitrogen in the soil. The nutrient component in the EPIC model generates data for the estimation of the stochastic nitrogen carry-over rate function. This function is estimated by using the nitrogen mass balance framework in the nutrient component.

The nitrogen mass balance component in the EPIC model is formulated as a system of equations (Table 1). Inputs to crop production include commercial nitrogen applications (FN), nitrogen from precipitation (NPRCP), and nitrogen fixation (NFIX) (Eq. (i)). Nitrogen is removed from the system through removal of the crop harvested (YLN), subsurface flow (SSFN), percolation (PRKN), surface runoff (YNO_3), denitrification (DN), and volatilization (AVOL) (Eq. (ii)). The net change in nitrate (NO_3) due to transformation through mineralization of soil organic nitrogen to nitrate and immobilization of nitrate to organic nitrogen is estimated as the change in the quantity of organic nitrogen in the active pool (ORG N AC) and in the stable pool (ORG N ST) from period t to period $t+1$ minus all organic nitrogen loss in sediment in period t (YON) (Eq. (iii)). The nitrogen available for plant uptake (Eq. (iv)) is the initial nitrate level (NO_3) plus nitrogen inputs (Eq. (i)) adjusted for the organic change (Eq. (iii)) in the soil. The carry-over nitrate (Eq. (v)) in period $t+1$ is nitrogen available for plant uptake (Eq. (iv)) minus nitrogen

[8] EPIC was selected over other process models such as NLEAP and CREAMS (Shaffer, 1995) because these other models do not have the crop growth component. This component is essential for estimating yield response as a function of available nitrogen as well as nutrient mass balance. The latter value is used in estimation of the carry-over rate function.

disappearance (Eq. (ii)). Nitrogen available for carry-over (Eq. (vi)) is nitrogen available for uptake (Eq. (iv)) less nitrogen in the harvested crop (YLN).

The nitrogen mass balance component in the EPIC model can be validated by comparing the annual carry-over nitrogen amounts, $NO_{3(t+1)}$, estimated by Eq. (v) in period t with the realized annual carry-over nitrogen amount generated by the EPIC model in period $t+1$. The annual nitrogen carry-over rate is the ratio of Eq. (v) divided by Eq. (vi). The EPIC model generated annual carry-over rates and the corresponding amounts of nitrogen available for plant uptake are used in the estimation of the expected carry-over function.

5. Determination of the optimal nitrogen fertilizer application rate for corn grown at the ARS demonstration farm in southern Maryland

Use of soil N-testing can be one component of a best nutrient management practice designed to help a farmer determine the amount of nitrogen fertilizer to apply in order to maintain the optimal level of nitrogen in the soil available for plant uptake. Assuming an objective of maximizing the present value of expected farm net income, the optimal level of nitrogen that must be maintained in the soil must be determined. In what follows, this is done for corn grown at the USDAs Agricultural Research Service Sustainable Agriculture Demonstration Farm in southern Maryland. The steps involved in this determination include EPIC model simulations, estimation of the expected yield function and expected nitrogen carry-over rate function using EPIC-generated data, and the application of the dynamic rule (relationship (5)) to determine the required optimal steady-state nitrogen level in soil available for plant uptake.

5.1. EPIC model simulations

Version 5300 of the EPIC model was employed to simulate production of continuous corn on a hypothetical farm modeled after the Sustainable Agriculture Demonstration Farm at the USDA's Beltsville Agricultural Research Center, a 6-acre site on the South Farm operated by the Agricultural Research Service. The Demonstration Farm has a complex soil with slope varying between 2% and 15%. In the EPIC model simulations, Sassafras soil, one of the soil types present at this site, with an 8% slope was used. Weather records from Owings Ferry Landing in southern Maryland were also used. It was assumed that corn is continuously planted. This was assumed since it is one of the common practices in corn production and it uses more nitrogen fertilizer per acre than any other cropping practice (Gill and Padgitt, 1995). The farmer is assumed to use PSNT annually with the soil N-test being conducted at the end of May to determine the amount of nitrogen in the soil. Based on relationship (5), the farmer then computes the amount of nitrogen to be applied at the beginning of June for side-dressing. In the EPIC model simulations, the farmer must apply 22.4 kg per hectare of nitrogen fertilizer (10-20-10) annually at the time of planting (at the beginning of April) in addition to the amount of nitrogen fertilizer (28-0-0) applied at the beginning of June that is determined based on the results of the soil N-test.

As noted previously, the EPIC model for corn was used because it has been extensively validated across a wide range of soil types and weather conditions in different parts of the United States. Rigorous statistical validation of the EPIC model for the Sustainable Agriculture Demonstration Farm, however, was limited by the lack of the requisite field-level data. Consequently, validation was based on a comparison of nitrogen fertilizer use efficiency between EPIC model simulation results and the results from actual corn production at the Demonstration Farm. A soil scientist familiar with the site was also consulted. Corn grown after soybeans at the Sustainable

Agricultural Demonstration Farm produced an average yield of 11.30 mt/ha (180 bu/ac) for 205 kg/ha (183 lb/ac) of fertilizer nitrogen applied in 1994 (Lu and Kelly, 1994). The nitrogen use efficiency, which is the amount of nitrogen in the yield divided by the amount of nitrogen applied (Meisinger et al., 1992) was 72%. In contrast, an EPIC model simulation covering 20 years produced an average yield of 9.57 mt/ha (153 bu/ac) from continuous corn production for the same amount of nitrogen fertilizer applied at the Sustainable Agriculture Demonstration Farm. The nitrogen fertilizer use efficiency in this instance is 61%. [9] For the well known reasons, a lower nitrogen fertilizer use efficiency is expected for the continuous planting of corn than for corn in rotation with soybeans. The EPIC model simulation results show an average nitrogen loss of 15 kg/ha through leaching and an average nitrogen loss of 75 kg/ha in sediment. It was concluded that these EPIC model simulation results were within a reasonable range for that site after consultation with a soil scientist familiar with the site.

5.2. Estimation of the expected yield function and the expected nitrogen carry-over rate function

The EPIC model was used to simulate continuous corn production for 20 years for each of the following levels of nitrogen fertilizer application rates: 160, 170, 180, 190, 200, 210, and 220 kg per hectare. Twenty years of EPIC model simulation results for each of the seven nitrogen fertilizer application rates were used in the estimation of the yield response function. In each EPIC model simulation, the annual average amount of nitrate in the soil at the end of May (determined by soil N-testing) plus the amount of nitrogen fertilizer applied determine the amount of nitrogen available for plant uptake. A Mischerlich-type functional specification with an asymptotic yield plateau was used in the estimation of the yield function. Yield is simply specified as a function of the amount of nitrogen available for plant uptake. This plateau function has been shown to describe adequately the relationship between yield response and nitrogen in the soil (Beattie and Taylor, 1985; Cerrato and Blackmer, 1990). The exact functional specification is given as $y = a_1(1 - \exp(a_2 r))$, where y is yield, r the nitrogen available for plant uptake at the end of May, and a_1 and a_2 are coefficients to be estimated. As noted previously, r is just the sum of nitrogen carried over from the previous year plus nitrogen applied in the current year.

Results from the EPIC model simulations of the seven rates of nitrogen fertilizer application were also used to estimate the expected nitrogen carry-over rate function. The annual average carry-over rate and the annual average nitrogen available for plant uptake were used in the estimation of the expected nitrogen carry-over rate function. Annual carry-over rates were determined by the ratio of the estimated amount of nitrogen carried over at the end of May to the amount of residual nitrogen available for carry-over from the previous year using Eq. (vi) in Table 1. A simple linear model was specified such that $v = b_1 + b_2 r$ for the expected nitrogen carry-over rate function. The variable v is the carry-over rate and r is the amount of nitrogen available for plant uptake while b_1 and b_2 are coefficients to be estimated.

Since there is some potential gain in estimation efficiency, a nonlinear seemingly unrelated regression technique was used in the estimation of the coefficients of the yield function and the carry-over rate function in deference to estimating the coefficients of the relationships individually using classical least-squares techniques (Davidson and Mackinnon, 1993). Estimation results for the yield function and the carry-over rate function are given in Table 2.

[9] Note that yields and nitrogen fertilizer application rates from the Demonstration Farm and from the EPIC simulations are slightly different than the average yield and application rates observed in production agriculture in Maryland. Annual corn yields in Maryland vary significantly. The average corn yield (1991–1993) was 100 bushel per acre (Agricultural Statistics, 1994). The average nitrogen fertilizer application rate was 110 pounds per acre and nitrogen use efficiency was 73%.

Table 2
Estimated coefficients on the corn yield function for continuous planting of corn and the expected nitrogen carry-over function

Parameter	Estimate	t statistic [a]
a_1	9.6069	408.51
a_2	−0.0163	−19.52
b_1	0.9101	21.533
b_2	−0.0004	−3.023

[a] In examining the statistical significance of the estimated coefficients, a simple t-test is appropriate because each observation used in the estimation represents an average value of the 20-year simulations results from the EPIC model. The average values are normally distributed as a consequence of the law of large numbers (Pfeiffer, 1965).

The pseudo-R^2 (coefficient of determination) for the yield equation is 0.87 while for the nitrogen carry-over rate equation it is 0.56. Thus, the variation in nitrogen available for plant uptake explains about 87% of the total variation in yield. Although nitrogen available for plant uptake is an important factor in the EPIC model yield determination, there are other factors, such as weather and water stress conditions during the growing period that can influence yield. Variation in these factors is not explicitly reflected in any variable in the yield function and hence are captured in the unexplained residual. The results also indicate that as the amount of nitrogen in the soil available for plant uptake increases, the decline in the nitrogen carry-over rate is relatively small. This decline, however, is statistically significantly different from zero at the 5% level.

There is one additional interesting result from the estimation. It was assumed in developing the relationship for the optimal amount of nitrogen available for plant uptake that yield and the nitrogen carry-over rate are independent. The credibility of this assumption is confirmed in the empirical results. Using the estimated variance–covariance matrix from the nonlinear seemingly unrelated regression, one finds the covariance between the yield function and the nitrogen carry-over rate function to be less than 40% of the variance in the yield function. Moreover, there is very little gain in estimate efficiency as a consequence of using the nonlinear seemingly unrelated regression approach instead of classical least squares. A comparison of the two sets of coefficient estimates using the different estimation approaches [10] reveals than none of the estimated coefficients differ by more than 5% and none of these differences is statistically significantly different from zero at the 5% level.

5.3. Optimal nitrogen recommendations

Using the estimated expected yield function and the estimated expected nitrogen carry-over function in conjunction with GAMS (General Algebraic Modeling System) (Brook et al., 1987), it is possible to solve empirically the dynamic programming problem of maximizing the present value of expected net farm income (i.e., relationship (1)) subject to the carry-over function (i.e., relationship (4)) for the optimal level of nitrogen in the soil available for plant uptake and the optimal nitrogen fertilizer application rate. (Note that empirically solving relationship (5) will yield the same results as solving relationship (1) subject to relationship (4).) The current period and expected next-year price of nitrogen fertilizer are assumed to be equal to \$0.66 per kg (\$0.20/lb). The expected price of corn is assumed to be \$98.44 per ton (\$2.50/bu). The discount

[10] Complete results of this comparison are available upon request.

Table 3
Results from dynamic and static rules including results from EPIC simulation using the steady-state nitrogen application rate

	Dynamic rule (A)	EPIC simulation (B)	Percent difference (B − A)/A × 100	Static rule (C)	Percent difference (C − A)/A × 100
Net farm income ($/ha) [a]	814.51	820.20 (32) [b]	0.7	799.00	−1.9
Yield (ton/ha)	9.48	9.52 (0.33)	0.4	9.20	−2.9
N-applied (a^*) (kg/ha)	180.66	180.66 (0)	0.0	161.48	−10.6
N-carry-over (x^*) (kg/ha)	86.91	84.06 (9)	−3.3	34.28	−60.5
N-available (r^*) (kg/ha)	267.57	262.06 (9)	−0.2	195.76	−24.8
N-loss (w^*) [c] (kg/ha)	21.31	22.00 (5)	3.0	6.93	67.5

[a] Net farm incomes under dynamic and static rules are the steady-state undiscounted values, while net farm income under EPIC is the average undiscounted value from 17-years simulation. The values of the first three years are deleted to avoid the effect of the initial conditions.
[b] The figure in the parentheses is the standard deviation of the estimate.
[c] N-loss does not include the loss of organic N initially in the soil. Nitrogen loss from the EPIC model simulations is computed by the equation

$$\underset{22(\text{kg/ha})}{\text{N-loss}} = \underset{(3)}{\text{PRKN}} + \underset{(0)}{\text{DN}} + \underset{(2)}{\text{SSFN}} + \underset{(0)}{\text{AVOL}} + \underset{(2)}{\text{YNO}_3} + (\underset{(76)}{\text{YON}} - \underset{(61)}{\text{ORG-N changes}}).$$

The definitions of these terms are given in Table 1.

rate is assumed to be 7%. The optimal steady-state nitrogen level in the soil for plant uptake at the end of May is 267 kg/ha and the optimal steady-state optimal nitrogen fertilizer application rate is 180 kg/ha (160 lb/ac). [11] The results are shown in column 1 in Table 3. The nitrogen carry-over rate at the steady state is 0.804.

Is the GAMS's optimal solution close to the EPIC model's optimal solution obtained when applying the nitrogen fertilizer at the optimal application rate ($a^* = 180.66$ kg/ha) annually? Theoretically, as noted previously, the optimal nitrogen fertilizer application rate from both should be identical because both assume the same expected yield and expected carry-over rate functions. Practically, since numerical algorithms are involved in the estimation and simulation processes, the values would be expected to be slightly different due to the vagaries of rounding. To see just how different they are, EPIC model simulations were conducted for different nitrogen fertilizer application rates within the range of 160–220 kg/ha. Results from these EPIC model simulations show that the steady-state optimal nitrogen fertilizer application rate (180.66 kg/ha in Table 3) is *de facto* in the range of the optimal application rates that can be determined from EPIC model simulations. [12] The negligible difference between the average net farm income as determined by GAMS and the EPIC model simulations indicates that the optimal nitrogen fertilizer application rate estimated by either of the two approaches can be used by the farmer who seeks to maximize the present value of expected net farm income.

Can the steady-state optimal amount of nitrogen that needs to be available for plant uptake ($r^* = 268$ kg/ha) be used to compute the optimal nitrogen fertilizer application rate recommendation based on soil N-testing? To answer this question, EPIC model simulations using nitrogen fertilizer application recommended rates ranging between 240 and 280 kg/ha based on soil N-testing were investigated. In each simulation, the EPIC model was run for one year at a time for 20 years. At the end of each year (May), a soil N-test was conducted and the test information used to

[11] The optimal rate includes 22.4 kg/ha of nitrogen fertilizer applied at the time of planting.
[12] The difference in net farm income under different application rates in the range is relatively small.

determine the amount of supplemental nitrogen fertilizer that needed to be applied based on the recommended rate. [13] The EPIC model simulation results [14] indicate that the steady-state optimal nitrogen fertilizer application rate is within the range of the optimal solution. Therefore, the results of soil N-testing can credibly be used.

Finally, will it make a significant difference if, instead of the dynamic rule, the static rule, which ignores the value of carry-over nitrogen, is used to determine the recommended nitrogen fertilizer application rate? The static rule determines the optimal nitrogen application rate by equating the value of the marginal product of fertilizer to the expected fertilizer price. That is, the static rule states $\alpha E[p_t^y]\partial E[y_t]/\partial a_t = p_t^f$. (Drop the second term on the right-hand side of Eq. (5).) By applying this rule, the optimal static "steady-state" application rate is determined. (Note the implicit assumption that the nitrogen carry-over is constant. [15]) The optimal static steady-state solution is shown in Table 3. A farmer adopting the static rule will use significantly less nitrogen fertilizer than one using the dynamic rule. This results in a smaller net farm income but a significantly smaller nitrogen loss.

6. Benefits of soil N-tests

An important issue in the fertilizer application decision is precisely what is the benefit to the farmer (private benefit) and what is the benefit to the environment (social benefit) of soil N-testing. In what follows, these benefits will be estimated. The benefits of soil N-test are measured by the difference in net farm income (private benefit) and the difference in nitrogen loss (social benefit) between when a soil N-test is used and when no soil N-test is employed. The EPIC model is used to evaluate the benefit of soil N-testing to the profit-maximizing corn farmer under the following seven scenarios: (1) annual nitrogen fertilizer applications based on the results of soil N-testing (the benchmark), (2) an annual fixed application rate (180 kg/ha) based on the correct expected nitrogen carry-over rate, (3) an annual fixed application rate based on a 20% over-estimate of the correct carry-over rate, (4) an annual fixed application rate based on a 25% under-estimate of the correct carry-over rate, (5) an annual fixed application rate based on a 50% under-estimate of the correct carry-over rate, (6) an annual application rate based on yield goals of the past three-year yield average, and (7) an annual fixed application rate based on an expected plateau-yield goal. In scenario 1, the farmer uses soil N-test results to estimate the nitrogen fertilizer application rate needed to have the optimal amount of nitrogen available for plant uptake during the growing season. In scenarios 2–5, the farmer systematically overestimates or underestimates the application rate. These four scenarios are designed to show that the benefits of soil N-testing to the profit-maximizing farmer depends on the farmer's knowledge about the nitrogen carry-over rate of the field. In scenario 6, the farmer uses prior yield information to determine the yield goal associated with a nitrogen fertilizer application rate. Annual application rates are based on 1.2 times the yield goal, where 1.2 is the amount of nitrogen required to produce a bushel of corn that is consistent with a yield based on the average of the yields in the previous

[13] The authors are grateful to Veral Benson at the Blackland Research Center, Temple, Texas, for showing how to run EPIC when the soil N-testing is involved.

[14] The simulation results are shown in scenario 1 (Benchmark scenario) in Table 4.

[15] The optimal static "steady-state" application rate can be determined in two iterations. First, assign an arbitrary value for initial nitrogen in the soil and solve the static rule for the optimal solution. The nitrogen carry-over function (4) is used to determine the amount of carry-over nitrogen for the next period. Second, with this carry-over nitrogen as an initial condition for the second time period, solve the static rule again to again to obtain the optimal static steady-state nitrogen carry-over level and application rate.

Table 4
EPIC model simulation results for various nitrogen fertilizer management scenarios

Scenarios	1	2	3	4	5	6	7
N-soil testing used	yes	no	no	no	no	no	no
Avg Application Rate (FN) (kg/ha)	178 (22) [a]	180 (0)	166 (0)	192 (0)	196 (0)	182 (4)	206 (0)
Average Yield (ton/ha)	9.54 (0.33)	9.55 (0.33)	9.43 (0.32)	9.57 (0.34)	9.57 (0.33)	9.55(0.33)	9.57 (0.34)
Net Farm Income [b] ($/ha)	816 (38) [c]	820 (33)	818 (32)	816 (33)	812 (33)	820 (33)	806 (33)
Nitrogen leached (PRKN) (kg/ha)	2.3 (2.5)	3.3 (3.3)	2.3 (2.3)	6 (6)	8 (8)	4 (4)	15 (12)
Nitrogen in sediment (YON) (kg/ha)	70 (45)	74 (47)	72 (46)	75 (48)	75 (48)	71 (46)	75 (48)
Nitrogen denitrification (DN) (kg/ha)	0.4 (0.5)	0.5 (0.5)	0.2 (0.3)	1.0 (0.2)	1.0 (0.2)	0.6 (0.5)	1.0 (0)
Nitrogen in subs flow (SSFN) (kg/ha)	2 (0.6)	2.0 (0.7)	1.6 (0.7)	2.6 (0.8)	2.6 (0.8)	2.3 (0.8)	3.3 (0.9)
Nitrogen surface runoff (YNO_3) (kg/ha)	1.5 (1.4)	1.5 (1.2)	1.3 (1.0)	1.7 (1.5)	1.7 (1.5)	1.6 (1.4)	1.7 (1.6)
Organic N depletion (kg/ha)	55 (45)	58 (48)	62 (45)	56 (49)	54 (49)	55 (46)	54 (49)
Nitrogen Loss [d] (kg/ha)	21 (7)	23 (8)	15 (9)	32 (9)	35 (10)	24 (8)	42 (14)

[a] Figures in parenthesis are standard deviation of the estimates.
[b] The average of 20-years annual farm income in current (undiscounted) dollars.
[c] The cost of N-testing is included in net farm income. It is about $ 6/ha.
[d] Nitrogen Loss = PRKN + DN + SSFN + YNO_3 + (YON − ORG − N change).

three years. [16] In scenario 7, the farmer determines the application rate using an unbiased expected plateau-yield goal. The application rate is based on the amount of nitrogen needed to achieve an expected plateau yield. [17] Scenarios 6 and 7 compare two common rule-of-thumb nutrient management practices frequently used in the absence of soil N-testing. In each scenario, 22.4 kg/ha of nitrogen (10-20-10) of the total amount of nitrogen to be applied is applied at the time of planting at the beginning of April.

6.1. Soil N-testing (benchmark) scenario

With soil N-testing, the farmer at period $t = 1$ uses soil N-testing to indicate the amount of carry-over nitrogen in the soil at the end of May before side-dressing is applied in early June. Based on the soil N-test results, supplemental nitrogen fertilizer (28-0-0) is added to the soil to maintain 268 kg/ha of nitrogen in the soil at the end of May. This is the steady-state optimal amount of nitrogen that should be available for plant uptake, as determined by the dynamic rule (relationship (5)). The EPIC model is run for one year at a time for 20 years. At the end of May in each crop year, a soil N-test is conducted and the test results are used to determine the amount of supplementary nitrogen fertilizer needed. A summary of the 20-years of simulation results is shown under scenario 1 in Table 4. The average net farm income is $816/ha (with a standard deviation of 38). Included in this is a reduction of $6/ha for the cost of soil N-testing based on Bosch et al. The nitrogen losses from leaching sediment, denitrification, volatilization, and subsurface flow and surface runoff are also shown in Table 4. Total nitrogen losses (N-loss), excluding the organic nitrogen initially in the soil, is 21 Ib/ac (with a standard deviation of 7). [18]

[16] The efficiency factor of 1.2 is typically used in calculating the nitrogen fertilizer application rate for a given corn yield (Blackmer et al., 1992; Meisinger et al., 1992).

[17] The nitrogen fertilizer application rate is estimated by 1.2 times the expected plateau yield. This is 9.607 mt/ha based on the estimated yield function (Table 2).

[18] The results in Table 4 indicate that nitrogen loss at the Sustainable Agriculture Demonstration Farm comes mainly from organic nitrogen loss via sediment (70 kg/ha/yr). This results primarily from the depletion of soil organic matter (55 kg/ha/yr) initially in the soil. Nitrogen losses from nitrate leaching, denitrification, subsurface flow and surface runoff, volatilization are relatively small.

6.2. Correctly estimate nitrogen carry-over rate scenario

Next, assume the farmer annually applies the optimal steady-state application rate, 180 kg/ha, as determined by the dynamic rule using the correct nitrogen carry-over rate (0.804). The EPIC model simulation results are shown under scenario 2 in Table 4. The average annual net farm income is \$820 per hectare (with a standard deviation of 33) and the average annual nitrogen loss is 23 kilograms per hectare (with a standard deviation of 8). The farmer switching to soil N-testing will lose \$4/ha of net farm income, but will reduce nitrogen loss by 2 kg/ha. The tradeoff between net farm income loss and nitrogen loss reduction is an obvious dilemma posing a tradeoff for the farmer (private loss) and society (public gain).

6.3. Overestimate the nitrogen carry-over rate by 20% scenario

When the nitrogen carry-over rate is systematically overestimated by 20%, the farmer applies 166 kg/ha of nitrogen fertilizer annually. This is the optimal steady-state nitrogen application rate estimated by GAMS assuming a 20% overestimate of the correct nitrogen carry-over rate. This value is used as the fixed value in the EPIC model simulations. The EPIC model simulation results are shown under scenario 3 in Table 4. By moving from this scenario to the benchmark (i.e., adopting soil N-testing), the farmer will loose \$2/ha in net farm income and will increase nitrogen loss by 6 kg/ha. In this instance both the farmer and society are better off not using soil N-testing.

6.4. Underestimate the nitrogen carry-over rate by 25% scenario

When the nitrogen carry-over is systematically overestimated by 25%, the farmer applies 192 kg/ha of nitrogen fertilizer annually. The EPIC model simulation results are shown under scenario 4 in Table 4. Moving from this scenario to the benchmark will result in a decrease of 11 kg/ha in nitrogen loss but with no change in net farm income although there is a slight change in income variability. Under this scenario, a farmer will be unaffected but society will be better off using soil N-testing to reduce nitrogen losses.

6.5. Underestimate the nitrogen carry-over rate by 50% scenario

When the nitrogen carry-over rate is underestimated by 50%, the farmer applies 196 kg/ha of nitrogen fertilizer. The EPIC model simulation results are shown under scenario 5 in Table 4. By moving from this scenario to the benchmark, the farmer will gain \$4/ha in net farm income and also reduce nitrogen loss by 14 kg/ha. Both the farmer and society are in a win–win situation with the adoption of soil N-testing in this instance.

6.6. Nitrogen fertilizer application rate based on an average-yield goal scenario

The EPIC model was run annually for 20 years to obtain the average net farm income and the average nitrogen loss based on a yield goal. The yield goal for the determination of annual nitrogen application rate is based on the average yields obtained over the previous three years. The EPIC model simulation results are shown under scenario 6 in Table 4. The average nitrogen fertilizer application rate is 182 kg/ha. Moving from this scenario to the N-soil testing benchmark results in a \$4/ha decrease in net farm income with a corresponding contraction by 3 kg/ha in nitrogen loss. The tradeoff between the net farm income reduction and the decrease in nitrogen loss creates a dilemma that the farmer and society must confront if this scenario is adopted.

6.7. Nitrogen fertilizer application rate based on an expected plateau-yield goal scenario

Using an expected plateau-yield goal, simulations using the EPIC model were carried out for 20 years to obtain the average annual net farm income and the average annual nitrogen loss. The annual nitrogen application rate is 206 kg/ha based on an expected maximum yield of 9.607 mt/ha (see footnote 12). The EPIC model simulation results are shown under scenario 7 in Table 4. The farmer will realize an increase in net farm income of \$10/ha and there will be a corresponding decrease in nitrogen loss of 21 kg/ha if this scenario is abandoned and soil N-testing adopted. The farmer and society are in a win–win situation with the adoption of soil N-testing under this scenario.

7. Conclusions

The economic benefits to the farmer and the environmental benefits to society associated with soil nitrogen testing by a profit-maximizing farmer depend on the farmer's knowledge about nitrogen carry-over as well as current nitrogen management practices. In the foregoing analysis, a dynamic fertilizer use decision model has been combined with a crop production process model to evaluate the economic and environmental benefits of pre-side-dress soil N-testing for a hypothetical risk-neutral farmer growing corn at the USDAs Agricultural Research Service Sustainable Agriculture Demonstration Farm site in southern Maryland. For the farmer who is knowledgeable about expected nitrogen carry-over, adoption of soil N-testing may lead to a reduction in net farm income but it may also precipitate a reduction in nitrogen losses to the environment. For the farmer currently overestimating the expected nitrogen carry-over rate by more than 20%, soil N-testing will not lead to a reduction in nitrogen loss but it may lead to an improvement in net farm income. For the farmer currently underestimating the expected nitrogen carry-over rate by more than 25%, soil N-testing will help reduce nitrogen losses and lead to an improvement in net farm income. For the farmer who uses a three-year average-yield goal to determine the annual nitrogen fertilizer application rate, use of soil N-testing will help reduce nitrogen loss but it will not result in any improvement in net farm income. Soil N-testing, however, will help the farmer who uses an expected plateau-yield goal improve net farm income and reduce nitrogen loss significantly.

While there are differences in the impact on net farm income of the various nutrient management scenarios not relying on soil N-testing relative to the benchmark which is based on soil N-testing (with the exception of scenario 7), these differences are simply too small to ensure that soil N-testing can lead to an improvement or reduction in net farm income. This is because of the relatively large fluctuations in net farm income attributable to the variability in the weather.

Use of soil N-testing does not reduce the variation (standard deviations) in net farm income and nitrogen loss. This is highlighted in Table 4. If the farmer is risk-averse, the soil N-testing will not mitigate the variability in net farm income. The small differences in net farm income and in the variation in net farm income as measured by the standard deviation across scenarios can be explained by the fact that the weather conditions during the growing season have a stronger effect on crop yield than any differences in the amount of nitrogen fertilizer applied. Thus, the results from this study do not support the argument that there are unequivocal positive benefits from using soil N-testing for either the farmer or society.

Finally, the results do suggest that soil N-testing is a valuable tool that can be used to improve net farm income and reduce nitrogen loss for the farmer currently applying nitrogen fertilizer based on an expected plateau-yield goal. The results suggest that soil N-testing can be beneficial to the farmer by leading to an enhancement in net farm income and to society by leading to reduced nitrogen loss if the farmer has underestimated the nitrogen carry-over rate by more than 25%. If soil N-testing is to be a useful tool to improve water quality in the study area, farmers underestimating nitrogen carry-over rate by more than 25% should be targeted. If soil N-testing is to be promoted as an important method in reducing nonpoint source pollution in the nation, a procedure to identify these farmers in the win–win situation through, for example, surveys to assess field-level nitrogen mass balance and the use of the evaluation method presented in this study will have to be developed.

Appendix A. Derivation of the stochastic rule for the optimal nitrogen fertilizer application rate

The derivation of the stochastic rule for the optimal nitrogen fertilizer application rate follows Kennedy's direct dynamic programming method. The crop yield response in period t is $y_t(r_t, \delta_t)$ where r_t is nitrogen available for plant uptake in period t and δ_t is a random variable. The percent of residual nitrogen to be carried over from period t to $t+1$, V_t, is given as $v_t(w_t, r_t, \varepsilon_t)$ where w_t is a site-specific variable and ε_t is a random variable. The problem is to maximize the expected net farm income

$$\max_{a_1 \ldots a_n} \quad \sum_{t=1}^{n} \alpha^{t-1} E[\alpha P_t^y y_t(r_t, \delta_t) - p_t^f a_t], \tag{A.1}$$

$$\begin{aligned} \text{s.t.} \quad & r_t = x_t + a_t, \\ & x_{t+1} = v_t(r_t, w_t, \varepsilon_t)(r_t - \kappa y_t(r_t, \delta_t)), \\ & a_t \geqslant 0 \\ & \text{with } x_1 \text{ given.} \end{aligned} \tag{A.2}$$

The recursive equation of the dynamic programming problem (A.1) and (A.2) is

$$\zeta_t\{x_t, p_t^y, p_t^f\} = \max_{a_t} \quad E[\alpha p_t^y y_t(r_t, \delta_t) - p_t^f a_t + \alpha \zeta_{t+1}\{x_{t+1}, p_{t+1}^y, p_{t+1}^f\}] \text{ for } t = n, \ldots, 1 \tag{A.3}$$

$$\begin{aligned} \text{s.t.} \quad & r_t = x_t + a_t, \\ & x_{t+1} = v_t(r_t, w_t, \varepsilon_t)(r_t - \kappa y_t(r_t, \delta_t)), \\ & a_t \geqslant 0. \end{aligned} \tag{A.4}$$

with

$$x_1 \text{ given } \zeta_{n+1}\{x_{n+1}, p_{n+1}^y, p_{t+1}^f\} = 0 \tag{A.5}$$

The dynamic programming problem Eqs. (A.3)–(A.5) also can be expressed as

$$\zeta_t\{x_t, p_t^y, p_t^f\} = \alpha E[p_t^y y_t(x_t + a_t^*, \delta_t) - p_t^f a_t^*] \quad + \alpha \zeta_{t+1}\{E[x_{t+1}, p_{t+1}^y, p_{t+1}^f]\} \quad \text{for } t = 1, \ldots, n, \tag{A.6}$$

where $a_1^* \ldots a_n^*$ are the optimal rates, and $x_{t+1} = v_t(x_t + a_t^* - \kappa y(x_t + a_t^*, \delta_t))$.

Assuming that function (A.3) is concave, partial differentiation of (A.3) with respect to a_t gives the first-order condition for an interior maximum. This is given as

$$\alpha E[p_t^y] \partial E[y_t(x_t, \delta_t)]/\partial a_t - p_t^f + \alpha E[(\partial x_{t+1}/\partial a_t)(\partial \zeta_{t+1}/\partial x_{t+1})] = 0 \quad \text{for } t = 1, \ldots, n. \tag{A.7}$$

Next, partial differentiation of (A.3) with respect to x_t gives

$$\partial \zeta_t / \partial x_t = \alpha E[p_t^y] \partial E[y_t(r_t, \delta_t)]/\partial a_t + \alpha E[(\partial x_{t+1}/\partial a_t)(\partial \zeta_{t+1}/\partial x_{t+1})] \quad \text{for } t = 1, \ldots, n, \tag{A.8}$$

where $\partial y_t/\partial a_t$ is evaluated at $x_t + a_t^*$. Since the terms on the right-hand side of Eq. (A.8) equal p_t^f as shown in Eq. (A.7), (A.8) becomes

$$\partial\zeta_t/\partial x_t = p_t^f. \tag{A.9}$$

Substituting p_{t+1}^f for $\partial\zeta_{t+1}/\partial x_{t+1}$, and $v_t(w_t, \varepsilon_t)(r_t - \kappa y_t(r_t, \delta_t))$ for x_{t+1} in Eq. (A.7) gives

$$\alpha E[p_t^y]\partial E[Y_t(n_t, \delta_t)]/\partial a_t = p_t^f - \alpha E[\partial v_t(r_t, w_t, \varepsilon_t)(r_t - \kappa y_t(n_t, \varepsilon_t))]/\partial a_t p_{t+1}^f \quad \text{for} \quad t = 1, \ldots, n. \tag{A.10}$$

Now, assume that the price of nitrogen fertilizer and the nitrogen carry-over rate are independent, and that the current nitrogen fertilizer price is known and that the future nitrogen fertilizer price is a random variable conditional on the price from the previous year. Given these assumptions, for a specific field (drop w_t because it is fixed), (Eq. (A.10)) becomes

$$\alpha E[p_t^y]\partial E[y_t(r_t, \delta_t)]/\partial a_t = p_t^f - \alpha\partial E[(v_t(r_t, \varepsilon_t))(r_t - \kappa y_t(r_t, \delta_t))]/\partial a_t E[p_{t+1}^f \mid p_t^f] \quad \text{for } t = 1, \ldots, n. \tag{A.11}$$

With the assumption of independence between the nitrogen carry-over rate and residual nitrogen, Eq. (A.11) becomes

$$\alpha E[p_t^y]\partial E[y_t(r_t, \delta_t)]/\partial a_t = p_t^f - \alpha\partial(E[v_t(r_t, \varepsilon_t)](r_t - \kappa E[y_t(r_t, \delta_t)]))/\partial a_t E[p_{t+1}^f \mid p_t^f] \quad \text{for } t = 1, \ldots, n. \tag{A.12}$$

For $t = 1$, the optimal amount of nitrogen available for plant uptake, r_t^* can be determined from Eq. (A.12) and the optimal nitrogen fertilizer application rate, a_t^*, is the difference between r_t^* and the given initial amount of nitrogen in the soil, x_t.

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