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Economic and Environmental Feasibility of Variable Rate Nitrogen Fertilizer Application with Carry-Over Effects

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This study evaluates the long-term profitability and environmental impacts of variable rate versus uniform nitrogen application in seed potato production with nitrogen carry-over effects included. Seed potato yields were simulated for four different areas of a field using the EPIC crop growth model. A dynamic optimization model was used to determine optimal steady-state nitrogen levels for each area and the entire field. Average nitrogen losses and economic returns were evaluated for both uniform and variable rate nitrogen fertilizer. Variable rate nitrogen application was found to be unprofitable for the field when compared to uniform nitrogen application. Nitrogen losses for the field were about the same under both strategies. The results indicate greater economic and environmental benefits may be achieved by splitting nitrogen applications, especially for areas of the field exhibiting low yield productivity.

Key words: dynamic optimization, nitrogen carry-over, nitrogen loss, profitability, variable rate application

Introduction

The traditional method of agricultural input application is to treat the entire field as one homogeneous unit and apply the input uniformly throughout the field in one fixed rate. This method ignores spatial variations in soil type, soil fertility, and yield potential that are likely to be present in the field. As a result, the input is underapplied in some areas and overapplied in other areas. Variable rate application refers to the application of agricultural inputs in specific and changing rates throughout the field. The goal of variable rate application is to apply a precise amount of fertilizers, pesticides, water, seeds, or other inputs to specific areas in the field where and when they are needed for crop growth. Variable rate application has the potential to increase both agricultural productivity and environmental stewardship. However, this practice must be shown to be profitable before farm operators will adopt it.

The economic feasibility of variable rate application has not been fully explored. To date, the economic studies that have been conducted have produced mixed results, leaving the profitability issue unresolved (Lowenberg-DeBoer and Boehlje; Lu et al.). Most studies focus solely on fertilizer application and use a partial budgeting framework

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to evaluate the returns and costs associated with variable rate application (e.g., Carr et al.; Fiez, Miller, and Pan; Hammond; Hayes, Overton, and Price; Hertz and Hibbard; Wibawa et al.; Wollenhaupt and Buchholz). Nearly all of the profitability studies use yield goals and fertilizer recommendations to determine the amount of fertilizer to be applied. However, fertilizer application based on yield goals and fertilizer recommendations may not necessarily lead to maximum net returns.

In addition, most earlier investigations ignore the effects of variable rate input application on the environment. A notable exception is a recent study by Schnitkey, Hopkins, and Tweeten, who evaluated the profitability of variable rate phosphorous and potassium application for a corn-soybean rotation. They used dynamic programming (DP) to account for soil nutrient carry-over from year to year and to determine optimal steady-state nutrient rates for each crop in the rotation. The authors compared the returns from variable rate application to its costs and found it to be profitable for all 20 fields evaluated in their study. Their results also indicated variable rate application of phosphorous and potassium would lead to lower average nutrient levels when compared to uniform application, and therefore result in less nutrient loss from the field.

The objective of this analysis is to determine the long-term economic and environmental feasibility of variable rate nitrogen fertilizer application for a specific field situation given nitrogen carry-over effects. Variable rate application of nitrogen fertilizer is the focus of this investigation primarily because most crops use more nitrogen than any other nutrient, and because nitrogen is highly water soluble and therefore more likely to leach into groundwater than other nutrients (Hallberg; Lee and Nielsen; Spalding and Exner). Seed potato is selected for this study because it is a high-value product and profitability from variable rate application may be easier to achieve for higher value crops (Lowenberg-DeBoer and Boehlje). A dynamic optimization model is used to determine optimal steady-state nitrogen fertilizer rates for different parts of a field near Ashton, Idaho, exhibiting spatial seed potato yield variability. As in Schnitkey, Hopkins, and Tweeten, we evaluate variable rate fertilizer application for a rotation rather than a monoculture setting. However, this study differs from Schnitkey, Hopkins, and Tweeten in two ways. First, we evaluate variable rate application for nitrogen fertilizer only. Second, we evaluate variable rate nitrogen fertilizer application for only the cash crop (seed potatoes) rather than for every crop in the rotation.

Proper assessment of the long-term economic and environmental impacts of variable rate nitrogen application requires long-term crop yield and nitrogen movement data. Since variable rate application is still in its infancy, no such data are available. Until these data become available, crop simulation models may be used to evaluate the long-term impacts of variable rate application (Lowenberg-DeBoer and Swinton; Lu et al.). We use the EPIC crop growth model to estimate crop yields and nitrogen losses for different parts of the field under uniform and variable rate nitrogen fertilizer application.

Site Description of Field

This study is based on actual farm-level production data from a seed potato operation near Ashton, Idaho. The area under study is a 63-hectare field composed of Kucera silt loam with bedrock substratum and Lostine silt loam soils. Both soils are classified as being well drained, moderately permeable, and possessing high water-holding capacity [U.S. Department of Agriculture (USDA), Soil Conservation Service]. The typical rotation used on this field is a three-year seed potato/spring wheat/feed barley sequence, with seed potatoes planted in early May and harvested in early October, and the two grain crops planted in early April and harvested in late August. Seed potato yields were monitored across the field in October 1995, using a load cell type yield monitor system similar in design to that reported in Rawlins et al. The resulting data indicate seed potato yields for 1995 ranging from less than 6 Mg ha^{-1} in some areas to over 22 Mg ha^{-1} in other areas. This information was used to group seed potato yields into the following four ranges:

- YldR1 = below 6 Mg ha^{-1} (5 ha),
- YldR2 = between 6 and 11 Mg ha^{-1} (21 ha),
- YldR3 = between 11 and 17 Mg ha^{-1} (31 ha), and
- YldR4 = greater than 17 Mg ha^{-1} (6 ha).

A dynamic optimization model is used to determine optimal steady-state nitrogen fertilizer levels for each yield range and the field during the potato year of the rotation. In the next two sections, we present this model and explain how it was used to derive optimal steady-state nitrogen fertilizer levels for each part of the field.

The Dynamic Optimization Model

Potatoes are grown in rotation with other crops for pest management reasons. In Idaho, seed potatoes may be rotated with as many as two or three other crops in three- and four-year rotations. Small grain crops such as wheat and barley are the typical crops used in these rotations, and often are not individually profitable. They are grown primarily for pest management benefits, and as such represent expenses to seed potato production. Consequently, seed potatoes may have greater potential to benefit from variable rate nitrogen application than the other crops used in the rotation.

Historically, a three-year seed potato/spring wheat/feed barley rotation has been used on the 63-hectare study field. Assume the farm operator uses variable rate nitrogen fertilizer application during the seed potato year, but uses conventional nitrogen fertilizer application during the wheat and barley years. As noted earlier, most studies evaluating the profitability of variable rate fertilizer application use yield goals and fertilizer recommendations to determine the optimal amount of fertilizer to be applied. However, fertilizer should be applied at the level at which the value of the marginal product of fertilizer is equal to the price of fertilizer. Furthermore, when there are carry-over effects (e.g., fertilizer applied in the current season promotes crop growth in the current and subsequent seasons), the optimization rule must be revised to maximize the present value of net returns from a sequence of crops (Kennedy).

Both Taylor and Kennedy show how dynamic optimization models can be used to determine optimal fertilizer application rates for continuous cropping systems with fertilizer carry-over. We have modified the Taylor model to determine optimal nitrogen fertilizer application rates for the three-year seed potato rotation. For the sake of simplicity, assume the amounts of nitrogen applied in the wheat and barley years are held constant at their historical averages.[1] Given the decision maker desires to maximize the expected value of profit for the rotation, the recursive equation for optimal nitrogen application during the potato crop year can be expressed as:

$$(1)\quad \begin{aligned} &F_k\left(R^P_{k,t},\, R^W_{k,t+1},\, R^B_{k,t+2};\, P^P_t,\, P^W_{t+1},\, P^B_{t+2};\, r_t,\, r_{t+1},\, r_{t+2}\right) \\ &= \underset{A^P_{k,t}}{\text{Max}}\, E\Big[P^P_t Y^P_{k,t}\left(N^P_{k,t},\, \rho^P_{k,t}\right) - r_t A^P_{k,t} \\ &\qquad + \alpha P^W_{t+1} Y^W_{k,t+1}\left(N^W_{k,t+1},\, \rho^W_{k,t+1}\right) - \alpha r_{t+1} A^W \\ &\qquad + \alpha^2 P^B_{t+2} Y^B_{k,t+2}\left(N^B_{k,t+2},\, \rho^B_{k,t+2}\right) - \alpha^2 r_{t+2} A^B \\ &\qquad + \alpha^3 F_{k+1}\Big(R^P_{k+1,t+3},\, R^W_{k+1,t+4},\, R^B_{k+1,t+5}; \\ &\qquad\qquad P^P_{t+3},\, P^W_{t+4},\, P^B_{t+5};\, r_{t+3},\, r_{t+4},\, r_{t+5}\Big)\Big], \end{aligned}$$

subject to:

$$(2)\quad \begin{aligned} N^P_{k,t} &= A^P_{k,t} + R^P_{k,t}, \\ N^W_{k,t+1} &= A^W + R^W_{k,t+1}, \\ N^B_{k,t+2} &= A^B + R^B_{k,t+2}; \end{aligned}$$

$$(3)\quad \begin{aligned} R^W_{k,t+1} &= V^P_{k,t}\left(N^P_{k,t},\, \delta^P_{k,t}\right), \\ R^B_{k,t+2} &= V^W_{k,t+1}\left(N^W_{k,t+1},\, \delta^W_{k,t+1}\right), \\ R^P_{k+1,t+3} &= V^B_{k,t+2}\left(N^B_{k,t+2},\, \delta^B_{k,t+2}\right); \end{aligned}$$

$$(4)\quad A^P_{k,t} \geq 0, \quad \text{with } R^P_{11} \text{ given},$$

where

$F_k(\cdot)$ = the expected present value of crop sequence k (k = potato/wheat/barley), with variables in parentheses representing state variables;

t = the crop year;

E = the expectation operator;

$Y^P_{k,t}(\cdot)$, $Y^W_{k,t+1}(\cdot)$, $Y^B_{k,t+2}(\cdot)$ = stochastic production functions for potato, wheat, and barley, respectively;

P^P_t, P^W_{t+1}, P^B_{t+2} = crop prices;

[1] Actually, fertilizer application generally is based on an annual soil test for the field and some desired yield goal. Thus nitrogen fertilizer application varies somewhat from year to year for all crops in actual practice. For this study, we hold nitrogen fertilizer application constant during the wheat and barley years, since we are concerned primarily with optimal nitrogen fertilizer application during the potato year only, when application rates are allowed to vary for different areas of the field.

$N_{k,t}^P$, $N_{k,t+1}^W$, $N_{k,t+2}^B$ = available nitrogen fertilizer identities for each crop year;
$R_{k,t+1}^W$, $R_{k,t+2}^B$, $R_{k+1,t+3}^P$ = residual soil nitrogen carry-over levels for each crop year;
$V_{k,t}^P(\cdot)$, $V_{k,t+1}^W(\cdot)$, $V_{k,t+2}^B(\cdot)$ = stochastic nitrogen carry-over functions for each crop year;
$A_{k,t}^P$, A^W, A^B = amounts of nitrogen fertilizer applied in each crop year;
r_t = the price of nitrogen fertilizer in crop year t;
$\rho_{k,t}^P$, $\rho_{k,t+1}^W$, $\rho_{k,t+2}^B$, $\delta_{k,t}^P$, $\delta_{k,t+1}^W$, $\delta_{k,t+2}^B$ = random variables; and
α = the time preference discount factor equal to $1/(1+d)^t$, where d equals the discount rate.

Subscripts k and t are excluded from A^W and A^B because nitrogen application rates in the wheat and barley years of the crop sequence are each assumed constant and equal to their historical averages, as noted earlier. The stochastic dynamic economic model above represents the objective function of a risk-neutral farmer who wants to determine the optimal nitrogen fertilizer application rate that maximizes the present value of expected net farm income. While risk neutrality is commonly assumed for farmers in most dynamic programming studies, this assumption excludes the impacts of intertemporal (between-year) and intratemporal (within-year) risk faced by farmers when making agricultural decisions. Krautkraemer, van Kooten, and Young show how both intertemporal and intratemporal risk may be incorporated into dynamic programming models.

The problem above can be solved recursively beginning with the last crop sequence in the planning horizon and working backwards through time. Assuming no terminal value for residual soil nitrogen, (1) can be expressed as:

(5)
$$\begin{aligned} &F_K\left(R_{K,T-2}^P, R_{K,T-1}^W, R_{K,T}^B; P_{T-2}^P, P_{T-1}^W, P_T^B; r_{T-2}, r_{T-1}, r_T\right) \\ &= \max_{A_{K,T-2}^P} E\Big[P_{T-2}^P Y_{K,T-2}^P\left(N_{K,T-2}^P, \rho_{K,T-2}^P\right) - r_{T-2}A_{K,T-2}^P \\ &\quad + \alpha P_{T-1}^W Y_{K,T-1}^W\left(N_{K,T-1}^W, \rho_{K,T-1}^W\right) - \alpha r_{T-1}A^W \\ &\quad + \alpha^2 P_T^B Y_{K,T}^B\left(N_{K,T}^B, \rho_{K,T}^B\right) - \alpha^2 r_T A^B\Big], \end{aligned}$$

where K represents the last crop sequence in the planning horizon, and T represents the last crop year in the planning horizon. Assuming current prices are known and expected prices in period T can be determined by prices in period $T-1$, expansion of the expectation operator in (5) gives:

(6)
$$\begin{aligned} &F_K\left(R_{K,T-2}^P, R_{K,T-1}^W, R_{K,T}^B; P_{T-2}^P, P_{T-1}^W, P_T^B; r_{T-2}, r_{T-1}, r_T\right) \\ &= \max_{A_{K,T-2}^P} \Big[P_{T-2}^P y_{K,T-2}^P\left(N_{K,T-2}^P\right) - r_{T-2}A_{K,T-2}^P \\ &\quad + \alpha E\left(P_{T-1}^W \mid P_{T-2}^W\right) y_{K,T-1}^W\left(N_{K,T-1}^W\right) - \alpha E\left(r_{T-1} \mid r_{T-2}\right)A^W \\ &\quad + \alpha^2 E\left(P_T^B \mid P_{T-1}^B\right) y_{K,T}^B\left(N_{K,T}^B\right) - \alpha^2 E\left(r_T \mid r_{T-1}\right)A^B\Big], \end{aligned}$$

where $y^P_{K,T-2}(N^P_{K,T-2})$, $y^W_{K,T-1}(N^W_{K,T-1})$, and $y^B_{K,T}(N^B_{K,T})$ represent the expected values of the potato, wheat, and barley production functions, respectively. Assuming these expected values are continuously differentiable and strictly concave, the optimal level of applied nitrogen fertilizer, $A^{*P}_{K,T-2}$, can be obtained by solving the first-order condition:

$$(7)\qquad \frac{\partial F_K}{\partial A^P_{K,T-2}} = P^P_{T-2}\left(\frac{\partial y^P_{K,T-2}}{\partial N^P_{K,T-2}}\right)\left(\frac{\partial N^P_{K,T-2}}{\partial A^P_{K,T-2}}\right) - r_{T-2} + \alpha E\left(P^W_{T-1} \mid P^W_{T-2}\right)\left(\frac{\partial y^W_{K,T-1}}{\partial N^W_{K,T-1}}\right)\left(\frac{\partial N^W_{K,T-1}}{\partial A^P_{K,T-2}}\right) + \alpha^2 E\left(P^B_T \mid P^B_{T-1}\right)\left(\frac{\partial y^B_{K,T}}{\partial N^B_{K,T}}\right)\left(\frac{\partial N^B_{K,T}}{\partial A^P_{K,T-2}}\right) = 0.$$

From the identities in (2), it can be seen that

$$(8)\qquad \frac{\partial N^P_{K,T-2}}{\partial A^P_{K,T-2}} = 1.$$

Likewise,

$$(9)\qquad \frac{\partial N^W_{K,T-1}}{\partial A^P_{K,T-2}} = \frac{\partial N^W_{K,T-1}}{\partial N^P_{K,T-2}}$$

and

$$(10)\qquad \frac{\partial N^B_{K,T}}{\partial A^P_{K,T-2}} = \left(\frac{\partial N^B_{K,T}}{\partial N^W_{K,T-1}}\right)\left(\frac{\partial N^W_{K,T-1}}{\partial N^P_{K,T-2}}\right).$$

Thus, the first-order condition for profit maximization of (7) is expressed as:

$$(11)\qquad \frac{\partial F_K}{\partial A^P_{K,T-2}} = P^P_{T-2}\left(\frac{\partial y^P_{K,T-2}}{\partial N^P_{K,T-2}}\right) - r_{T-2} + \alpha E\left(P^W_{T-1} \mid P^W_{T-2}\right)\left(\frac{\partial y^W_{K,T-1}}{\partial N^W_{K,T-1}}\right)\left(\frac{\partial N^W_{K,T-1}}{\partial N^P_{K,T-2}}\right) + \alpha^2 E\left(P^B_T \mid P^B_{T-2}\right)\left(\frac{\partial y^B_{K,T}}{\partial N^B_{K,T}}\right)\left(\frac{\partial N^B_{K,T}}{\partial N^W_{K,T-1}}\right)\left(\frac{\partial N^W_{K,T-1}}{\partial N^P_{K,T-2}}\right) = 0.$$

The first term on the right-hand side of the equal sign in (11) is the value of seed potatoes obtained from a marginal unit of $A^P_{K,T-2}$ in year $T-2$, the second term is the price of nitrogen fertilizer in year $T-2$, the third term is the effect of a marginal unit of $A^P_{K,T-2}$ on the value of spring wheat in year $T-1$, and the fourth term is the effect of a marginal unit of $A^P_{K,T-2}$ on the value of feed barley in year T (the last period in the planning horizon). The optimal level of available nitrogen for potato crop year $T-2$ ($N^{*P}_{K,T-2}$) is found by solving (11) for some given level of residual soil nitrogen carry-over ($R^P_{K,T-2}$). The optimal nitrogen fertilizer application level for period $T-2$ ($A^{*P}_{K,T-2}$) can be calculated by subtracting $R^P_{K,T-2}$ from $N^{*P}_{K,T-2}$.

For the next-to-last crop sequence (crop sequence $K-1$), the DP recursive equation is written as:

$$
\begin{aligned}
(12)\quad & F_{K-1}\left(R^P_{K-1,T-5},\, R^W_{K-1,T-4},\, R^B_{K-1,T-3};\, P^P_{T-5},\, P^W_{T-4},\, P^B_{T-3};\, r_{T-5},\, r_{T-4},\, r_{T-3}\right) \\
&= \underset{A^P_{K-1,T-5}}{\text{Max}} \Big[P^P_{T-5}\, y^P_{K-1,T-5}\left(N^P_{K-1,T-5}\right) - r_{T-5} A^P_{K-1,T-5} \\
&\quad + \alpha E\left(P^W_{T-4} \mid P^W_{T-5}\right) y^W_{K-1,T-4}\left(N^W_{K-1,T-4}\right) - \alpha E\left(r_{T-4} \mid r_{T-5}\right) A^W \\
&\quad + \alpha^2 E\left(P^B_{T-3} \mid P^B_{T-4}\right) y^B_{K-1,T-3}\left(N^B_{K-1,T-3}\right) - \alpha^2 E\left(r_{T-3} \mid r_{T-4}\right) A^B \\
&\quad + \alpha^3 E\left(F_K\left(R^P_{K,T-2},\, R^W_{K,T-1},\, R^B_{K,T};\, P^P_{T-2},\, P^W_{T-1},\, P^B_T;\, r_{T-2},\, r_{T-1},\, r_T\right)\right)\Big],
\end{aligned}
$$

where $E(F_K(\cdot))$ in equation (12) represents the expected present value of profit for crop sequence K (the last crop sequence in the planning horizon) evaluated at the optimal level of available nitrogen for potato year $T-2$ ($N^{*P}_{K,T-2}$). The first-order condition for profit maximization of (12) is:

$$
\begin{aligned}
(13)\quad \frac{\partial F_{K-1}}{\partial A^P_{K-1,T-5}} &= P^P_{T-5}\left(\frac{\partial y^P_{K-1,T-5}}{\partial N^P_{K-1,T-5}}\right) - r_{T-5} \\
&\quad + \alpha E\left(P^W_{T-4} \mid P^W_{T-5}\right)\left(\frac{\partial y^W_{K-1,T-4}}{\partial N^W_{K-1,T-4}}\right)\left(\frac{\partial N^W_{K-1,T-4}}{\partial N^P_{K-1,T-5}}\right) \\
&\quad + \alpha^2 E\left(P^B_{T-3} \mid P^B_{T-4}\right)\left(\frac{\partial y^B_{K-1,T-3}}{\partial N^B_{K-1,T-3}}\right)\left(\frac{\partial N^B_{K-1,T-3}}{\partial N^W_{K-1,T-4}}\right)\left(\frac{\partial N^W_{K-1,T-4}}{\partial N^P_{K-1,T-5}}\right) \\
&\quad + \alpha^3 E\left(r_{T-2} \mid r_{T-3}\right)\left(\frac{\partial v^B_{K-1,T-3}}{\partial N^B_{K-1,T-3}}\right)\left(\frac{\partial N^B_{K-1,T-3}}{\partial N^W_{K-1,T-4}}\right)\left(\frac{\partial N^W_{K-1,T-4}}{\partial N^P_{K-1,T-5}}\right) = 0.
\end{aligned}
$$

The first four terms to the right of the equal sign in (13) are defined as those in (11), while the last term represents the monetary savings in nitrogen fertilizer applications during potato year $T-2$ obtained from the marginal unit of nitrogen fertilizer in potato year $T-5$ ($A^P_{K-1,T-5}$). The term $v^B_{K-1,T-3}$ in (13) is the expected residual nitrogen carry-over to potato year $T-2$ in crop sequence K as a function of available nitrogen in barley year $T-3$ in crop sequence $K-1$ (i.e., $v^B_{K-1,T-3} = v^B_{K-1,T-3}(N^B_{K-1,T-3}) = E(R^P_{K,T-2} | N^B_{K-1,T-3})$. By induction, (13) may be expressed as

$$\frac{\partial F_k}{\partial A^P_{k,t}} = P_t\left(\frac{\partial y^P_{k,t}}{\partial N^P_{k,t}}\right) - r_t + \alpha E\left(P^W_{t+1} | P^W_t\right)\left(\frac{\partial y^W_{k,t+1}}{\partial N^W_{k,t+1}}\right)\left(\frac{\partial N^W_{k,t+1}}{\partial N^P_{k,t}}\right)$$
$$+ \alpha^2 E\left(P^B_{t+2} | P^B_{t+1}\right)\left(\frac{\partial y^B_{k,t+2}}{\partial N^B_{k,t+2}}\right)\left(\frac{\partial N^B_{k,t+2}}{\partial N^W_{k,t+1}}\right)\left(\frac{\partial N^W_{k,t+1}}{\partial N^P_{k,t}}\right)$$
$$+ \alpha^3 E\left(r_{t+3} | r_{t+2}\right)\left(\frac{\partial v^B_{k,t+2}}{\partial N^B_{k,t+2}}\right)\left(\frac{\partial N^B_{k,t+2}}{\partial N^W_{k,t+1}}\right)\left(\frac{\partial N^W_{k,t+1}}{\partial N^P_{k,t}}\right) = 0 \tag{14}$$

for every crop sequence but the last (i.e., for $k < K$). Thus, (14) can be used to solve for $N^{*P}_{k,t}$ and $A^{*P}_{k,t}$ for all but the last crop sequence in the planning horizon. As in the continuous cropping optimization problem outlined by Taylor, (14) does not have to be solved for every possible $R^P_{k,t}$. It only needs to be solved for one value of $R^P_{k,t}$ (the actual carry-over to period t). Also, the solution of (14) is necessary for only the time period for which the optimal application is to be determined, rather than for a sufficiently large number of time periods to assume convergence of the decision rule as with other DP models (Taylor).

The Steady-State Solution for the Dynamic Optimization Model

The optimal "steady-state" level of nitrogen available for plant uptake refers to the amount of nitrogen that must be maintained in the soil during the potato crop year (N^{*P}) to maximize expected net farm income. It is determined by making expected nitrogen and crop prices constant over time, and assuming all expected yield and expected nitrogen carry-over functions are invariant over time (e.g., $y^P = y^P_{k,t}$, $y^W = y^W_{k,t}$, and $y^B = y^B_{k,t}$; $v^P = v^P_{k,t}$, $v^W = v^W_{k,t}$, and $v^B = v^B_{k,t}$). A soil test for residual soil nitrogen would be required each potato crop year to determine the amount of applied nitrogen necessary to maintain N^{*P}. In the absence of a nitrogen soil test, the farm operator must exogenously determine the optimal steady-state nitrogen application rate for the potato crop year (A^{*P}) and apply this rate each potato crop year to maximize net farm income.

The optimal steady-state application rate for the potato year (A^{*P}) can be determined from relationship (14) by solving for just two crop sequences, $k = 1$ and $k = 2$. For $k = 1$, the optimal amount of nitrogen available for plant uptake in potato year $t = 1$ (N^{*P}_{11}) is obtained by solving (14) using initial condition R^P_{11}. The optimal steady-state level of available soil nitrogen to be maintained each potato year for profit maximization is represented by N^{*P}_{11}, which can be redesignated as N^{*P}. With N^{*P} known, the steady-state levels of nitrogen available for the wheat year (N^W) and the barley year (N^B) can be found. The optimal steady-state level of residual soil nitrogen carry-over to the potato year, R^{*P}, is equal to the expected level of residual soil nitrogen carry-over from the barley year of crop sequence $k = 1$ to the potato year of crop sequence $k = 2$, and is determined by inserting N^B into v^B [i.e., $E(R_{24}^P \mid N^B) = v^B(N^B) = R^{*P}$]. The optimal steady-state level of applied nitrogen in the potato year (A^{*P}) can be calculated by subtracting R^{*P} from N^{*P}.[2]

The optimal steady-state levels N^{*P}, A^{*P}, and R^{*P} should vary across the field if the field exhibits spatial yield variability. For example, crop yields may vary across the field due to spatial differences in soil texture, soil water-holding capacity, depth of topsoil, and organic matter content. The farm operator can use the optimal steady-state solutions to manage nitrogen application in one of two ways: (*a*) with a soil nitrogen test for the entire field in the potato year, or (*b*) with soil nitrogen tests in the potato year for all areas in the field exhibiting yield variability. The first strategy represents uniform nitrogen application, while the second represents variable rate nitrogen application. In both instances, the farm operator determines the amount of carry-over nitrogen available in the soil prior to fertilization ($R_{k,t}^P$) and applies the amount of nitrogen necessary to maintain N^{*P}. Thus, the optimal level of applied nitrogen either for the field or for each area of the field ($A_{k,t}^{*P}$) can vary for each potato year.[3]

If the costs of soil testing and fertilizer application remain the same for both uniform and variable rate application, the farm operator who applies nitrogen fertilizer variably across the field should obtain the maximum present value of net farm income over the planning horizon. These results occur because the farm operator who applies nitrogen variably across the field can maintain N^{*P} for each area of the field in every potato year. The N^{*P} for each area of the field cannot be maintained every potato year if nitrogen is applied uniformly, as the actual amount of nitrogen available for plant uptake in each area will be larger than N^{*P} in some potato years and smaller than N^{*P} in others. Consequently, because of diminishing marginal returns to nitrogen fertilizer, the farm operator who applies nitrogen fertilizer uniformly across the field will realize, ex post, a smaller aggregate net farm income. If, however, the costs of soil testing and fertilizer application are larger for variable rate application than for uniform application, then variable rate application will be more profitable than uniform application only if the benefits of maintaining N^{*P} for each area of the field in the potato year outweigh the additional costs of soil testing and fertilizer application.

If the factors affecting spatial yield variability are known, and if yield response functions and nitrogen carry-over functions can be estimated for each area of varying yield, then optimal steady-state solutions can be determined for different parts of the field. The EPIC crop growth model was used to simulate the data required to estimate yield response functions and nitrogen carry-over functions for each yield range and the field. The EPIC model and the methods used in this study are described in the next section.

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[2] If initial condition R_{11}^P is exceptionally large so that $A_{11}^{*P} = 0$, then the optimal steady-state nitrogen application rate for the potato year (A^{*P}) is determined by solving for three instead of two crop sequences (e.g., $A^{*P} = A_{37}^{*P}$ instead of A_{24}^{*P}).

[3] The farm operator also may apply nitrogen to potatoes without soil nitrogen testing. In the absence of soil nitrogen testing, the farm operator will apply nitrogen fertilizer either to the field or to different areas of the field at the optimal steady-state nitrogen application rate (A^{*P}). In this instance, the field or field area nitrogen application rate will be constant over time, since both N^{*P} and R^{*P} are constant.

Materials and Methods

Description of EPIC

EPIC (Environmental Policy Integrated Climate, formerly known as Erosion Productivity Impact Calculator) is a simulation model designed to help decision makers determine the impacts of alternative cropping systems and climate conditions on crop productivity, soil degradation, and water quality (Mitchell et al.). Its components include weather, hydrology, erosion, nutrient cycling, pesticide fate, soil temperature, tillage, crop growth, crop and soil management, and economics (Mitchell et al.; Williams 1989). The crop growth component simulates many crops using one crop growth model and unique parameter values for each crop (Williams et al.).

Nitrogen losses are simulated by the nutrient-cycling component of EPIC and include organic nitrogen transport in sediment and nitrate transport in runoff, percolation, and subsurface flow. An exponential function is used to estimate the decrease in nitrate concentration caused by water flow through a soil layer. The amounts of nitrate contained in runoff, percolation, and lateral flow are estimated as the products of the volume of water leaving the soil layer and the average daily concentration of nitrate in the soil layer; and a loading function is used to estimate organic nitrogen loss (Williams 1989).

EPIC Calibration

Two steps were taken to calibrate EPIC to simulate seed potato yields for the four yield ranges. The first was to calibrate EPIC to simulate a conventional three-year seed potato/spring wheat/feed barley crop sequence. This step was accomplished using soil data, farm production and management data, and daily weather data from the Ashton seed potato operation for the period 1987–94. The second step involved calibrating EPIC to simulate 1995 seed potato yields falling within each of the four yield ranges. In this step, EPIC simulations were made for the period 1987–95, and were sequenced so that a seed potato yield observation would be simulated for 1995. The simulations were made using actual daily weather data for 1987–95, and soil data for Kucera silt loam with bedrock substratum and Lostine silt loam soils. Calibrations for YldR1, YldR2, and YldR3 were made using Kucera silt loam soil data. The seed potato operator indicated that soil depths are variable across the field due to the bedrock substratum being close to the surface in many areas. Thus the model was calibrated for the first three yield ranges by reducing soil depths. Lostine silt loam soil data were used to simulate 1995 seed potato yields for YldR4. It must be noted that using three to five years of yield map data would be more appropriate for determining spatial patterns in yields for a particular field. However, only one year of seed potato yield map data was available for this study.

Irrigation, Weather Data, and Nitrogen Application

EPIC is used in this study to simulate crop yield and nitrogen loss data for each yield range over a 30-year period. Since irrigation water application does not vary by yield range in this study, each yield range should receive the same irrigation treatment each year. Thus, a base simulation was made by EPIC to establish a unique irrigation schedule for each simulation year. Kucera silt-loam with bedrock substratum soil data were used in the base run, since the majority of the field is composed of this soil type. Daily weather observations were generated by EPIC using monthly weather parameters calculated from Ashton daily weather data for the period 1988–95. The WXPARM weather parameter program (Williams 1996) was used to calculate the required parameters.

In the base run, all irrigation water was applied automatically using a center pivot system. Automatic irrigation of seed potatoes began on June 16 and continued until August 21, while automatic irrigation of spring wheat and feed barley began on June 6 and continued until July 24. The center pivot systems on the Ashton seed potato operation apply up to 1.9 cm of water per application, and require three days to make one complete application (or circuit). Based on this information, EPIC was programmed to apply 1.9 cm of water in three-day intervals whenever the plant water stress factor fell below 0.99. The maximum amount of water applied for each crop was 24 cm for the entire season, with an additional 2.5 cm of water applied to seed potatoes on September 21 to soften dirt clods for potato digging. The daily irrigation application output generated by the base run was used to establish the dates and amounts of irrigation water to be applied in each simulation year. These timings and amounts were held constant across all four yield ranges to ensure each yield range received the same irrigation treatment as would be the case in a whole-field situation.

Nitrogen and phosphorous in the base run were applied to each crop in elemental form prior to planting. Nitrogen applications were held constant at 102, 105, and 87 kg ha^{-1} for seed potatoes, spring wheat, and feed barley, respectively, while phosphorous levels were held constant at 41.5 kg ha^{-1} for seed potatoes and 11 kg ha^{-1} for spring wheat and feed barley. These amounts represent averages calculated from annual fertilizer application records provided by the Ashton seed potato operator for the period 1987–95. All nitrogen and phosphorous applications were incorporated to a depth of 15.2 cm.

Functions of Yield Response to Nitrogen

Yield response functions were estimated for all three crops by yield range. Sixteen nitrogen application levels were specified for potatoes in 11 kg increments ranging from 0 to 168 kg ha^{-1}. The rotation was simulated over a 30-year period for each potato nitrogen application, holding nitrogen applied to wheat and barley constant at their historical averages of 105 and 87 kg ha^{-1}, respectively. Two different methods of nitrogen application were evaluated for potatoes: (*a*) all nitrogen applied prior to planting, and (*b*) nitrogen applied in split applications. Both application methods are summarized in table 1. The postplant timings for nitrogen application in table 1 are based on suggested timings reported in Kleinkopf and Westermann. Preplant nitrogen applications were incorporated at a depth of 15.2 cm, while postplant nitrogen applications were incorporated at a depth of 1.27 cm. All postplant nitrogen fertilizer was assumed to be applied through the sprinkler system.

Simulated potato yields and soil nitrate-nitrogen (NO_3-N) carry-over at the end of April in the potato year were collected and averaged for each simulation. We assumed that a preplant nitrogen soil test would be used to determine the amount of NO_3-N in

Table 1. Nitrogen Application Strategies Used to Estimate Seed Potato Yield Response Functions (kg ha^{-1})

Preplant Strategy	Split N Strategy				Total N Applied
May 2	May 2	July 15	July 25	Aug 4	
0	0	0	0	0	0
11	0	11	0	0	11
22	0	22	0	0	22
34	0	34	0	0	34
45	0	34	11	0	45
56	0	34	22	0	56
67	0	34	34	0	67
78	0	34	34	11	78
90	0	34	34	22	90
101	11	34	34	22	101
112	22	34	34	22	112
123	34	34	34	22	123
134	45	34	34	22	134
146	56	34	34	22	146
157	67	34	34	22	157
168	78	34	34	22	168

the soil at the end of April. The average soil NO_3-N values were added to the amount of nitrogen applied to provide the average amount of available nitrogen for potato production for each simulation. The average yield data and the average available nitrogen data then were used to estimate potato yield response functions for each yield range and the entire field.

Yield response function data for wheat and barley were generated in a slightly different manner. Nitrogen applications to both wheat and barley were held constant rather than parameterized. Thus, only soil nitrogen carry-over was allowed to vary from year to year. Average available nitrogen for both crops was calculated as average soil NO_3-N carry-over at the end of March plus the fixed amount of nitrogen applied to each crop.

The estimated yield response functions are presented in table 2. A quadratic function was found to provide the best fit for the data. Other functional forms were examined, including the square root, the quadratic-plus-plateau, the Mitscherlich, and a logistic function. These functional forms either produced a poor fit relative to the quadratic function or predicted unrealistic optimal available nitrogen levels.[4] The potato yield response functions had the expected signs (i.e., a_0 and a_1 were positive; a_2 was negative). The wheat and barley functions had negative intercepts in most instances, because

[4] Optimal available nitrogen was calculated for each functional form by setting the marginal physical product equal to the ratio of nitrogen price to crop price (i.e., the static rule for nitrogen optimization). This was done as a check to exclude functional forms predicting unrealistic optimal available nitrogen levels.

Table 2. Quadratic Functions of Yield Response to Available Nitrogen by Crop and Yield Range

		Coefficients, Preplant N Strategy				Coefficients, Split N Strategy			
Yield Range	Crop	a_0	a_1	a_2	Adj. R^2	a_0	a_1	a_2	Adj. R^2
YldR1	Seed Potato	3.3699	0.1485	-0.0004	0.9993	2.9488	0.1659	-0.0004	0.9995
		(0.10482)	(0.00227)	(0.00001)		(0.09375)	(0.00202)	(0.00001)	
	Spring Wheat	-5.4978	0.1382	-0.0005	0.9973	-2.5214	0.0909	-0.0003	0.9910
		(0.31797)	(0.00500)	(0.00002)		(0.38158)	(0.00576)	(0.00002)	
	Feed Barley	-4.6710	0.1281	-0.0005	0.9999	-5.2244	0.1376	-0.0005	0.9995
		(0.19253)	(0.00363)	(0.00002)		(0.36847)	(0.00685)	(0.00003)	
YldR2	Seed Potato	3.8101	0.1954	-0.0005	0.9996	3.8038	0.1976	-0.0005	0.9998
		(0.09842)	(0.00202)	(0.00001)		(0.06773)	(0.00138)	(0.00001)	
	Spring Wheat	-1.8910	0.0860	-0.0003	0.9760	-1.4061	0.0787	-0.0002	0.9721
		(0.48649)	(0.00704)	(0.00003)		(0.47156)	(0.00675)	(0.00002)	
	Feed Barley	-4.3313	0.1218	-0.0005	0.9997	-3.9263	0.1145	-0.0004	0.9996
		(0.13012)	(0.00229)	(0.00001)		(0.13345)	(0.00233)	(0.00001)	
YldR3	Seed Potato	4.5822	0.2205	-0.0006	0.9994	4.7988	0.2195	-0.0006	0.9989
		(0.13583)	(0.00255)	(0.00001)		(0.17917)	(0.00336)	(0.00001)	
	Spring Wheat	-1.0024	0.0734	-0.0002	0.9709	-0.9637	0.0729	-0.0002	0.9659
		(0.43685)	(0.00595)	(0.00002)		(0.46206)	(0.00627)	(0.00002)	
	Feed Barley	-2.3211	0.0851	-0.0003	0.9990	-2.2679	0.0842	-0.0003	0.9989
		(0.12909)	(0.00207)	(0.00001)		(0.13312)	(0.00213)	(0.00001)	
YldR4	Seed Potato	10.5306	0.1755	-0.0004	0.9930	10.6111	0.1755	-0.0004	0.9909
		(0.42222)	(0.00644)	(0.00002)		(0.47716)	(0.00728)	(0.00002)	
	Spring Wheat	1.7775	0.0399	-0.0001	0.9491	1.7608	0.0401	-0.0001	0.9497
		(0.34232)	(0.00415)	(0.00001)		(0.34177)	(0.00415)	(0.00001)	
	Feed Barley	0.7128	0.0413	-0.0001	0.9963	0.6466	0.0422	-0.0001	0.9966
		(0.12810)	(0.00178)	(0.00001)		(0.12582)	(0.00175)	(0.00001)	
Field	Seed Potato	5.6091	0.2141	-0.0005	0.9990	5.7062	0.2136	-0.0005	0.9986
		(0.17485)	(0.00314)	(0.00001)		(0.20207)	(0.00363)	(0.00001)	
	Spring Wheat	-0.3651	0.0654	-0.0002	0.9455	-0.3432	0.0652	-0.0002	0.9365
		(0.50994)	(0.00681)	(0.00002)		(0.54235)	(0.00723)	(0.00002)	
	Feed Barley	-1.1120	0.0675	-0.0002	0.9945	-1.1219	0.0676	-0.0002	0.9943
		(0.19953)	(0.00310)	(0.00001)		(0.20198)	(0.00314)	(0.00001)	

Notes: Numbers in parentheses are standard errors of the coefficients. Number of observations = 16 for all yield response functions.

available nitrogen was not allowed to fall below 105 and 87 kg ha^{-1}, respectively. The remaining coefficients for the wheat and barley yield response functions had the expected signs.

Nitrogen Carry-Over

Nitrogen carry-over (NCO) to the current year is defined as some proportion of available nitrogen from the previous crop year. For example, NCO into the potato year is calculated as some proportion of available nitrogen in the barley year, and NCO into the barley year is calculated as some proportion of available nitrogen in the wheat year. The data used to estimate yield response functions also were used to estimate NCO rate functions.

NCO to the present period can vary depending on the crop grown in the previous period. Therefore, NCO rate functions were estimated for all three crops within each yield range. NCO rates were calculated as the ratio of average soil NO_3-N carry-over in the present period to average available nitrogen in the previous period. The rates then were specified as linear functions of available nitrogen in the previous crop year. NCO functions relating the portion of NCO to total nitrogen available less nitrogen removed in crop yield were found to produce poor fits to the data. These results probably occurred because much of the simulated NO_3-N carry-over to the next period was the result of mineralization of organic nitrogen into NO_3-N over time. Varvel and Peterson reported similar findings for two- and four-year grain rotations on silty clay loam soils near Mead, Nebraska. Their results suggested that most of the applied N for these cropping systems was immobilized by crop residues or soil organic matter, and was being released by mineralization at a later date.

The estimated nitrogen carry-over rate functions are presented in table 3. The seed potato and feed barley NCO rate functions were estimated using 16 observations, while the wheat NCO rate functions were estimated using 11 observations. The first five observations were excluded in estimating the latter functions, as levels of nitrogen applied in the potato year were too small to contribute much NCO for the wheat year. For these five observations, wheat year NCO was primarily a result of mineralization of organic N to nitrate N. The a_1 coefficients were positive for all NCO carry-over rate functions, indicating that the rate of nitrogen carry-over into the present year increases as available nitrogen in the previous year increases. The a_0 coefficients were positive for the spring wheat NCO rate functions, but were generally negative for the seed potato and feed barley NCO rate functions. The a_0 coefficients were negative for many of the latter functions because available nitrogen in the wheat and barley years was not allowed to fall below 105 and 87 kg ha^{-1}, respectively.

Nitrogen Application Strategies and Economic Data

The EPIC model was used to simulate crop yields and annual nitrogen losses in sediment, runoff, percolation, and subsurface flow for four different nitrogen fertilizer application strategies over a 30-year period. In all simulations, seed potatoes were rotated with spring wheat and feed barley. The four nitrogen application strategies are identified as follows:

Table 3. Nitrogen Carry-Over Rates as Linear Functions of Available Nitrogen in the Previous Year by Crop and Yield Range

		Coefficients, Preplant N Strategy			Coefficients, Split N Strategy		
Yield Range	Crop	a_0	a_1	Adj. R^2	a_0	a_1	Adj. R^2
YldR1	Seed Potato	-0.1466	0.0033	0.9964	-0.1307	0.0031	0.9941
		(0.00534)	(0.00005)		(0.00664)	(0.00006)	
	Spring Wheat	0.1588	0.0002	0.6321	0.1655	0.0006	0.9612
		(0.00773)	(0.00006)		(0.00536)	(0.00004)	
	Feed Barley	-0.0773	0.0018	0.9544	-0.0330	0.0014	0.9474
		(0.01262)	(0.00010)		(0.01121)	(0.00008)	
YldR2	Seed Potato	-0.0573	0.0026	0.9798	-0.0369	0.0024	0.9774
		(0.01084)	(0.00010)		(0.01048)	(0.00009)	
	Spring Wheat	0.0936	0.0011	0.9383	0.0982	0.0012	0.9495
		(0.01319)	(0.00009)		(0.01243)	(0.00008)	
	Feed Barley	-0.1142	0.0022	0.9512	-0.1129	0.0022	0.9462
		(0.01710)	(0.00013)		(0.01818)	(0.00013)	
YldR3	Seed Potato	0.0345	0.0021	0.9721	0.0373	0.0020	0.9715
		(0.01080)	(0.00009)		(0.01082)	(0.00009)	
	Spring Wheat	0.0962	0.0012	0.8304	0.1056	0.0012	0.8337
		(0.02607)	(0.00017)		(0.02528)	(0.00016)	
	Feed Barley	-0.1311	0.0025	0.9737	-0.1312	0.0025	0.9750
		(0.01505)	(0.00011)		(0.01472)	(0.00010)	
YldR4	Seed Potato	0.2807	0.0010	0.9550	0.2778	0.0010	0.9609
		(0.00753)	(0.00005)		(0.00717)	(0.00005)	
	Spring Wheat	0.1521	0.0011	0.8356	0.1712	0.0011	0.8345
		(0.02838)	(0.00016)		(0.02651)	(0.00015)	
	Feed Barley	0.0996	0.0014	0.9690	0.0995	0.0014	0.9695
		(0.01025)	(0.00006)		(0.01019)	(0.00006)	
Field	Seed Potato	0.0391	0.0022	0.9767	0.0391	0.0022	0.9803
		(0.01060)	(0.00009)		(0.00975)	(0.00008)	
	Spring Wheat	0.0724	0.0013	0.8062	0.0826	0.0012	0.8087
		(0.03134)	(0.00020)		(0.03027)	(0.00019)	
	Feed Barley	-0.1154	0.0025	0.9623	-0.1163	0.0025	0.9632
		(0.00251)	(0.00013)		(0.01800)	(0.00013)	

Notes: Numbers in parentheses are standard errors of the coefficients. Number of observations = 11 for spring wheat nitrogen carry-over rate function, and 16 for seed potato and feed barley nitrogen carry-over rate functions.

- CNV-PN: Conventional uniform nitrogen fertilizer application during the potato year, with nitrogen applied to potatoes in one preplant application;
- CNV-SN: Conventional uniform nitrogen fertilizer application during the potato year, with nitrogen applied to potatoes in split applications;
- VRA-PN: Variable rate nitrogen fertilizer application by yield range in the potato year, with nitrogen applied to potatoes in one preplant application; and
- VRA-SN: Variable rate nitrogen fertilizer application by yield range in the potato year, with nitrogen applied to potatoes in split applications.

Applied nitrogen for the single preplant application strategies was calculated as the difference between the optimal steady-state level of available nitrogen obtained from the DP model, N^{*P}, and the amount of nitrogen in the soil at preplant simulated by EPIC for the end of April in the potato year, $R^P_{k,t}$. We assumed the farm operator would determine $R^P_{k,t}$ using a soil nitrogen test. For the split nitrogen application strategies, preplant nitrogen was calculated by subtracting both $R^P_{k,t}$ and the fixed amount of post-plant nitrogen applied from N^{*P}.

The economic value of each nitrogen application strategy was calculated using the field-level net present value approach proposed by Hewitt and Lohr. The discrete form of the basic model for calculating net present value (NPV) for a rotation is as follows:

$$(15) \qquad NPV = \sum_{i=1}^{I} \frac{P_i Y_i - VC_i - AC_i}{(1 + d)^i},$$

where i equals the year in the rotation crop sequence, I equals the number of years in the complete crop sequence, P_i is the market price of the crop in the ith year (\$ unit^{-1}), Y_i is the annual yield of the crop in the ith year (units ha^{-1}), VC_i is the variable cost of producing the crop in the ith year (\$ ha^{-1}), AC_i is the annualized capital cost of yield monitor equipment in the ith year (\$ ha^{-1}), and d is the farmer's real discount rate.

Equation (15) represents the net present value of one complete rotation for a single field. This equation can be modified to calculate the net present value of the rotation into perpetuity, as follows (Hewitt and Lohr):

$$(16) \qquad NPV = \left[\sum_{i=1}^{I} \frac{P_i Y_i - VC_i - AC_i}{(1 + d)^i}\right]\left[\frac{1}{1 - (1 + d)^{-I}}\right].$$

The first term in equation (16) is the single rotation formula from equation (15), and the second term is the discounting effect of repeating the rotation to perpetuity. The annualized cash flow for a rotation discounted into perpetuity may be calculated by multiplying equation (16) by the real discount rate, d (Hewitt and Lohr).

Average crop yields from each 30-year simulation were used as steady-state yield estimates for each nitrogen application strategy. Market prices for each crop were calculated as five-year averages for the period 1991–95 (USDA, National Agricultural Statistics Service). The average price used for seed potatoes was \$105 Mg^{-1} (\$4.76 cwt^{-1}), the average price used for spring wheat was \$130 Mg (\$3.54 bu^{-1}), and that for feed barley was \$106 Mg^{-1} (\$2.31 bu^{-1}). Government program payments were excluded from the analysis as the 1996 Farm Bill legislation calls for a phaseout of farm income support after the year 2002.

A real discount rate of 4.2% was used for the net present value calculations. The real discount rate was calculated as the average prime rate of 7.3% for the period 1991–95 (Federal Reserve System) less an average inflation rate of 3.1% for the same period. Average inflation was calculated based on the Consumer Price Index (U.S. Department of Labor, Bureau of Labor Statistics).

Variable costs for each crop were obtained from University of Idaho Cooperative Extension Service enterprise budgets (Patterson, Ashley, and Smathers; Patterson, Gortsema, and Smathers; Patterson, Whitmore, and Smathers), and were supplemented with cost data from the Ashton seed potato operation. All variable cost data were in 1995 dollars. Variable costs included machinery operating costs, irrigation costs, costs of materials used in production (fertilizer, insecticide, seed), custom costs, consultation fees, crop insurance, operator labor costs, and interest on operating capital.

All fertilizer was custom applied. For the CNV strategies (CNV-PN and CNV-SN), the custom charge for fertilizer application was \$16.91 ha^{-1} and represented a \$12.35 ha^{-1} charge for conventional fertilizer application plus a \$4.57 ha^{-1} fee for soil testing. The latter charge was estimated assuming four soil samples were taken for the 63-hectare field (one every 16.2 hectares) at a cost of \$72 per sample (\$9 × 8 core samples per soil sample). Fertilizer application costs for wheat and barley under the variable rate strategies (VRA-PN and VRA-SN) remained the same as those under the conventional strategies. However, the fertilizer application charge for variable rate fertilizer application in the potato year was \$34.58 ha^{-1}. This charge was computed based on personal communications with fertilizer dealers in southern Idaho, and includes \$29.64 ha^{-1} for variable rate fertilizer application and \$4.94 ha^{-1} for map making.

Grid sampling is used in most instances to determine spatial soil nutrient content across the field. With grid sampling, the field is separated into grid cells of equal area. Soil samples are taken from each grid cell. The samples are analyzed in a laboratory, and the results are used to create soil nutrient maps for the field. We separated the field into four yield ranges to reduce the burden of simulating several grid cells. However, we account for grid sampling on the cost side. A grid sampling fee of \$44.45 ha^{-1} is charged to the VRA-PN and VSP-SN strategies. This charge was also calculated based on personal communications with southern Idaho fertilizer dealers, and includes \$24.70 ha^{-1} for grid soil sampling and \$19.75 ha^{-1} for soil analysis. All custom grid sampling charges were based on a grid size of 0.567 ha (1.4 acres).

For the variable rate strategies, we assumed the farm operator owns a potato yield monitor with a Differential Global Positioning System (DGPS) receiver. The cost of the yield monitor was \$2,700, while the cost of the DGPS receiver was \$3,500. The former fee represented a cost estimate from the Ashton, Idaho, farm operator for a new seed potato yield monitor, while the latter fee was the midpoint of the cost range for DGPS receivers reported in Lu et al.[5] An additional fee of \$500 was added to cover training costs (Lowenberg-DeBoer and Swinton). The total capital cost of equipment plus training was annualized to a per year expense of \$1,513 using the 4.2% real discount rate and a five-year replacement period. This expense then was converted to a per hectare expense of \$9.35 ha^{-1} $year^{-1}$, assuming the yield monitor would be used on 162 hectares of a typical 486-hectare seed potato operation.

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[5] We assume the farm operator obtains differential correction free of charge from a Coast Guard or Army Corps of Engineers station. However, differential correction often is obtained from commercial sources. The fee for this service ranges from \$250 to \$600 per year (Lu et al.).

Table 4. Custom Application Costs and Annualized Yield Monitor Capital Costs for Potato/Wheat/Barley Rotation by Fertilizer Application Method ($ ha^{-1})

	Nitrogen Application Strategies[a]	
Cost Item	CNV-PN / CNV-SN	VRA-PN / VRA-SN
Soil Testing / Analysis	4.57[b]	9.63[c]
Grid Soil Sampling	0.00	8.23[d]
Map Making	0.00	1.65[e]
Custom Application	12.35	18.11[f]
Annualized Yield Monitor Capital Cost	0.00	3.12[g]
Total	16.92	40.74

[a] CNV-PN = conventional nitrogen application in potato year, preplant N strategy; CNV-SN = conventional nitrogen application in potato year, split N strategy; VRA-PN = variable rate nitrogen application in potato year, preplant N strategy; and VRA-SN = variable rate nitrogen application in potato year, split N strategy.

[b] Four soil samples for the field at $72 per sample ÷ 63 hectares.

[c] $19.75 ha^{-1} VRA custom soil analysis charge for the region × 1/3 + $4.57 ha^{-1} conventional soil analysis charge × 2/3.

[d] $24.70 ha^{-1} VRA custom grid sampling charge for the region × 1/3.

[e] $4.94 ha^{-1} VRA custom map-making charge for the region × 1/3.

[f] $12.35 ha^{-1} custom charge for conventional fertilizer application × 2/3 + $29.64 ha^{-1} custom variable rate application charge for the region × 1/3.

[g] $9.35 ha^{-1} ($2,700 yield monitor cost + $3,500 DGPS receiver cost + $500 training cost annualized to an annual per hectare charge assuming a five-year replacement period, a 4.2% real discount rate, and the equipment is used on 162 hectares on a typical 486-hectare seed potato operation) × 1/3.

A summary of the per hectare cost of each fertilizer application method is provided in table 4. The CNV-PN and CNV-SN strategies have the smallest fertilizer application costs ($16.92 ha^{-1}), while VRA-PN and VRA-SN have the largest fertilizer application costs ($40.74 ha^{-1}).

Results

Optimal Steady-State Nitrogen Levels

Optimal steady-state levels of nitrogen available (N^{*P}), nitrogen applied (A^{*P}), and residual soil nitrogen (R^{*P}) in the potato crop year of the rotation were determined for this study using the DP optimization model presented by (1) above. The price of nitrogen fertilizer was held constant at $0.66 kg^{-1}, while crop prices were calculated as the average market prices reported above less per yield operating costs ($13.45 Mg^{-1} for seed potato storage, and $18.74 and $5.51 Mg^{-1}, respectively, for custom hauling of wheat and barley). The 4.2% real discount rate was used to calculate the time preference discount factor α. The model was solved for each yield range using the General Algebraic Modeling System (GAMS), version 2.25 (Brooke, Kendrick, and Meeraus).

The output of the model for the potato year of the rotation is presented in table 5. The amounts of plant available nitrogen required to maximize expected profits (N^{*P}) were

Table 5. Optimal Steady-State Nitrogen Levels for Potato Year by Yield Range

Strategy / Yield Range	Yield Range Area	N Available (N^{*P})	Total N Applied (A^{*P})	Residual Soil N (R^{*P})	Pre-plant N	Post-plant N	Yield (Y^{*P})
Preplant N:	[ha]			[kg ha^{-1}]			[Mg ha^{-1}]
YldR1	5	197	171	26	171	0	18.6
YldR2	21	190	155	35	155	0	22.9
YldR3	31	192	149	43	149	0	25.9
YldR4	6	199	134	65	134	0	28.3
Field	63	195	147	47	147	0	26.6
Split N:	[ha]			[kg ha^{-1}]			[Mg ha^{-1}]
YldR1	5	187	160	27	70	90	19.0
YldR2	21	188	153	35	64	90	22.8
YldR3	31	191	148	43	58	90	25.9
YldR4	6	198	133	65	44	90	28.3
Field	63	194	147	47	57	90	26.6

generally larger for the more productive yield ranges. YldR1 under the preplant N strategy was the exception to the rule. For this strategy, YldR1 required more plant available nitrogen to maximize expected profits (197 kg ha^{-1}) than either YldR2 (190 kg ha^{-1}) or YldR3 (192 kg ha^{-1}). This result was due to the shallow topsoil depth of YldR1 relative to the other four yield ranges. Much of the nitrogen applied to YldR1 percolated below the root zone. Therefore, more plant available nitrogen was required for profit maximization on YldR1 than on YldR2 or YldR3 under the preplant N strategy to replace nitrogen lost to percolation.

The steady-state levels of residual soil N carry-over (R^{*P}) were larger for the more productive yield ranges and smaller for the less productive yield ranges (table 5). These results were due to differences in organic carbon content and topsoil depth among the soils used for each yield range. The soil for YldR4 (Lostine silt loam) contained more organic carbon content than the soil used for the other three yield ranges (Kucera silt loam), allowing for more mineralization of organic N to nitrate N over time. The YldR4 soil also had the deepest topsoil depth, which made this soil the least susceptible to nitrate N losses from percolation. Both factors resulted in YldR4 having the largest R^{*P} value of the four yield ranges (65 kg ha^{-1} for both N application strategies). Conversely, the shallow soil depth of YldR1 precluded this yield range from having a large amount of soil N carry-over. Nitrogen not utilized by the plant tended to leach below the root zone on this yield range.

The split N strategy results imply that greater nitrogen application efficiency can be achieved for the field by splitting nitrogen application throughout the growing season rather than applying all nitrogen at preplant. As seen in table 5, both N^{*P} and A^{*P} were smaller under the split N strategy than under the preplant N strategy for nearly every instance, implying more efficient utilization of nitrogen by the plant under the former strategy. The greatest nitrogen application efficiency from the split N strategy occurred on YldR1, as would be expected given its shallow soil depth. Both N^{*P} and A^{*P} for YldR1 were reduced by 10 and 11 kg ha^{-1}, respectively, when using the split N strategy in place of the preplant N strategy.

For both nitrogen application strategies, uniform nitrogen application based on the field N^{*P} would result in less-than-optimal nitrogen fertilizer application to YldR1 and YldR2, more-than-optimal nitrogen fertilizer application to YldR4, and near-optimal nitrogen fertilizer application to YldR3. If the per hectare charges for fertilizer application in table 4 were constant for each application method, the farm operator would maximize profits by applying more nitrogen fertilizer to YldR1 and YldR2, and less nitrogen fertilizer to YldR4 than to the rest of the field. Also, results indicate that the amount of available N required to maximize expected profit for the field would be underestimated if nitrogen fertilizer recommendations were used. Based on agronomic recommendations, approximately 160 to 178 kg ha^{-1} available nitrogen would be required to achieve the optimal steady-state field yield of 26.6 Mg ha^{-1} when grain straw from the previous crop is incorporated (Love et al.; Painter et al.). These rates are smaller than those calculated for the field by the DP model (195 kg ha^{-1} for preplant N application, and 194 kg ha^{-1} for split N application).

Economic Returns by Nitrogen Application Strategy

Returns above variable costs, net present values, and annualized cash flows for each fertilizer application strategy are presented in table 6. Per hectare returns above variable costs were positive for the seed potato and the spring wheat years, but were negative for the feed barley year of the rotation in every case. The negative feed barley year return is not uncommon, as feed barley is included in the seed potato rotation for agronomic reasons rather than profitability.

Splitting application of nitrogen fertilizer in the potato year resulted in slight increases in annualized cash flow for the field under both conventional and variable rate fertilizer application (a \$2 ha^{-1} increase in cash flow using CNV-SN in place of CNV-PN, and a \$1 ha^{-1} increase in cash flow using VRA-SN in place of VRA-PN). The slightly larger cash flow for the field from split N application was due primarily to the increased cash flow from split N application on YldR1. The annualized cash flow on YldR1 was \$23 ha^{-1} larger for CNV-SN, and \$18 ha^{-1} larger for VRA-SN when compared to CNV-PN and VRA-PN. Split N application had little impact on the annualized cash flow of the other three yield ranges.

VRA-PN and VRA-SN were less profitable than the conventional strategies given the current cost structure (i.e., assuming the cost of all components in table 4 remain constant over time). For both VRA-PN and VRA-SN, the optimal level of plant available nitrogen was maintained for each yield range in the potato year. However, the total costs associated with variable rate fertilizer application (i.e., grid sampling, soil analysis, variable rate application, and the yield monitor) outweighed the benefits obtained from maintaining the optimal plant available nitrogen levels for each yield range. The costs used for variable rate application in the region are admittedly high relative to those reported in other crop-producing regions in the United States. Nonetheless, even if variable rate application costs for the region fell over time, VRA strategies would still likely be less profitable than conventional strategies for this field. Sensitivity analysis indicated that variable rate application costs would have to be reduced by 90% before the VRA-SN strategy would be as profitable as the CNV-SN strategy.

Table 6. Returns Above Variable Costs, Net Present Values, and Annualized Cash Flows by Nitrogen Application Strategy and Yield Range ($ ha^{-1})

Strategy / Yield Range	Returns Above Variable Costs: Potatoes	Wheat	Barley	NPV, Rotation [a]	Annualized Cash Flow, Rotation
CNV-PN:					
YldR1	87	16	-174	-55	-20
YldR2	503	84	-141	435	157
YldR3	788	123	-126	758	274
YldR4	990	168	-111	1,007	364
Field [b]	655	106	-134	608	220
CNV-SN:					
YldR1	143	21	-168	8	3
YldR2	503	84	-141	436	158
YldR3	786	123	-126	756	274
YldR4	990	168	-111	1,007	364
Field [b]	659	106	-133	613	222
VRA-PN:					
YldR1	50	20	-171	-85	-31
YldR2	438	86	-139	377	136
YldR3	716	124	-126	690	249
YldR4	921	167	-113	938	339
Field [b]	589	107	-133	546	198
VRA-SN:					
YldR1	92	23	-166	-37	-13
YldR2	439	86	-138	378	137
YldR3	713	124	-126	687	249
YldR4	921	167	-113	938	339
Field [b]	591	107	-132	549	199

[a] NPVs are calculated assuming a real discount rate of 4.2%.

[b] Returns for the field represent returns for YldR1–YldR4 weighted by the number of hectares for each yield range reported in table 5.

Nitrogen Losses by Nitrogen Application Strategy

Nitrogen losses associated with each application strategy are presented by crop and rotation in table 7. The crop N loss results indicate that most nitrogen loss for the rotation occurred during the potato and wheat years. The potato year resulted in the greatest N loss, as more nitrogen was applied in the potato year than in the other two years of the rotation. N losses in the wheat year were generally larger when the split N strategy was used during the potato year. The increased N losses during the wheat year are likely due to the inability of wheat to fully utilize the additional N carry-over resulting from split N application during the potato year.

Table 7. Total and Average Nitrogen Loss by Nitrogen Application Strategy and Yield Range (kg ha^{-1})

Strategy / Yield Range	N Loss by Crop:[a] Potatoes	Wheat	Barley	Total N Loss, Rotation	Average N Loss, Rotation
CNV-PN:					
YldR1	46	19	9	75	25
YldR2	11	17	7	35	12
YldR3	6	6	6	18	6
YldR4	9	8	9	26	9
Field[b]	11	11	7	29	10
CNV-SN:					
YldR1	28	26	10	63	21
YldR2	9	18	7	33	11
YldR3	5	6	5	17	6
YldR4	9	8	9	25	8
Field[b]	8	12	6	27	9
VRA-PN:					
YldR1	56	23	10	89	30
YldR2	13	19	7	39	13
YldR3	6	6	5	17	6
YldR4	9	7	8	25	8
Field[b]	13	12	7	31	10
VRA-SN:					
YldR1	33	29	10	72	24
YldR2	10	19	7	36	12
YldR3	5	6	5	17	6
YldR4	9	7	8	25	8
Field[b]	9	12	7	28	9

[a] N loss is the sum of average organic N loss from sediment, average nitrate N loss from runoff, average nitrate N loss from percolation, and average nitrate N loss from subsurface flow calculated from 30 years of EPIC-simulated data.

[b] Nitrogen losses for the field represent nitrogen losses from YldR1–YldR4 weighted by the number of hectares for each yield range reported in table 5.

N losses for the field were nearly the same between the conventional and the variable rate strategies (table 7), implying no environmental benefit was achieved by using variable rate nitrogen application in place of conventional nitrogen application on the field. The average N loss to the field was 10 kg ha^{-1} for both CNV-PN and VRA-PN; the corresponding N loss for both CNV-SN and VRA-SN was 9 kg ha^{-1}. Greater differences in N losses occurred between the preplant and the split N strategies. The preplant N strategies resulted in slightly larger N losses when compared to the split N strategies, and most of the N loss was attributable to YldR1. Average N losses on YldR1 were 25 kg ha^{-1} and 30 kg ha^{-1}, respectively, when using CNV-PN and VRA-PN, and were 21 kg ha^{-1} and 24 kg ha^{-1} when using CNV-SN and VRA-SN.

Summary and Conclusions

This study has investigated the economic and environmental outcomes associated with variable rate nitrogen fertilizer application considering carry-over effects for a specific field situation. A dynamic optimization model was used to determine optimal steady-state nitrogen levels for a field with spatially variable seed potato yields. The EPIC crop growth model was calibrated to simulate seed potato yields for four different areas of the field using soil, weather, and production data obtained from a seed potato operation near Ashton, Idaho. A three-year rotation of seed potatoes followed by spring wheat and feed barley was simulated over a 30-year period with conventional and variable rate nitrogen fertilizer application practiced during the potato year. Both preplant and split nitrogen application were examined in the analysis. Economic returns and average nitrogen losses were evaluated for each nitrogen application strategy assuming the farm operator desires to maximize expected profits and reduce nitrogen losses for the field.

If fertilizer application costs were the same under both conventional and variable rate application, the farm operator would receive a larger profit by applying variable rates of nitrogen fertilizer to each yield range. However, the costs of variable rate nitrogen application were much larger than those of conventional nitrogen application for the field. The larger fertilizer application costs outweighed the benefits achieved from maintaining the optimal steady-state level of plant available nitrogen for each yield range in the potato year. Also, there was little difference between average nitrogen losses for the field under variable rate application and those under conventional application. Thus minimal environmental benefit was achieved for the field from using variable rate nitrogen application. These results indicate that variable rate nitrogen application may not be appropriate for all field situations in which yields vary spatially.

The results also suggest that greater economic and environmental benefits may be achieved for some fields simply by improving the management of nitrogen fertilizer application. In all cases, split application of nitrogen fertilizer during the potato year was found to produce slightly larger profits and lower nitrogen losses for the field when compared to applying all nitrogen at preplant. The conventional strategy with split nitrogen application produced a larger profit for the field than the variable rate strategy with split nitrogen application. Most improvement in profit and reduced nitrogen losses from split nitrogen application occurred on the least productive yield range. This yield range had the most shallow topsoil depth. Split nitrogen application improved nitrogen utilization by the plant and reduced both the amount of optimal nitrogen applied and the amount of average nitrogen loss for this yield range.

Some caution must be used in interpreting the results of this study. The results apply to a specific field situation and cannot be generalized to a whole region. However, it may be argued that the economic and environmental feasibility of variable rate input application must be evaluated on a field-by-field basis, since the very nature of the technology is that it allows the farm operator to customize input application according to spatial variations in the field. It may be that the technology is profitable for a specific subset of field situations. The conclusions from our study indicate a need for more research in this direction. Also, complete disclosure of the cost structure of variable rate application should be made in profitability studies. Some studies report variable rate input application to be profitable, but do not account for or reveal all the costs associated with its use.

Several limitations of this study should be mentioned. One is that the model was calibrated to simulate crop yields for a seed potato operation, but was not calibrated to simulate nitrogen losses. In addition, neither yield output nor nitrogen loss output were validated. Despite these limitations, the results do seem to make sense given the known soil characteristics of the field. The nitrogen loss output may be interpreted in relative terms for each nitrogen application strategy (i.e., one nitrogen application strategy produces more N loss than another), as actual levels of nitrogen loss for the field are unknown.

A second limitation is that we explained spatial yield variability as a function of nitrogen availability and soil characteristics alone. However, yield variability is much more complex, and many factors contribute to it. A third limitation is that we used only one year of yield map data to measure spatial yield variability across the field. Four to five years of yield map data would be more appropriate for determining spatial patterns in yields for the field. Only one year's data were available for this study. Finally, we vary only one input. The profitability of variable rate application may be improved if other inputs, such as water, seeds, and pesticides, are varied in addition to fertilizer.

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