SITE-SPECIFIC MANAGEMENT

Economic Feasibility of Variable-Rate Nitrogen Application Utilizing Site-Specific Management Zones

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ABSTRACT

Variable-rate technology (VRT) has been developed to variably apply crop inputs to manage in-field variability. Although growers have begun to adopt VRT, its profitability is uncertain in N management. The objective of this study was to assess the economics of uniform vs. variable-rate N fertilizer application under two N application scenarios (farmer vs. custom applications). On-farm studies were conducted on two continuous corn (Zea mays L.) fields in northeastern Colorado under furrow and center-pivot irrigation during the 2000 and 2001 growing seasons. The N management strategies were uniform, grid-based, site-specific management zone–constant yield goal (SSMZ-CYG) and site-specific management zone–variable yield goal (SSMZ-VYG). “Profit and loss” software was used to analyze the economics of each N management strategy and determine which N strategy was most profitable. Results from three site-years consistently indicated that less total N fertilizer (6–46%) was used with the SSMZ-VYG N management strategy when compared with uniform N management. Net returns from the SSMZ-VYG N management strategy were $18.21 to $29.57 ha⁻¹ more than uniform N management. Results of this study suggest variable-rate N application utilizing site-specific management zones are more economically feasible than conventional uniform N application.

P R E C I S I O N F A R M I N G, or site-specific management, assists growers in making precise management decisions for different cropping systems throughout the world (Koch and Khosla, 2003). Site-specific management recognizes the inherent spatial variability associated with most fields under crop production (Thrikawala et al., 1999). Nitrogen, a highly mobile nutrient in the soil system, is one of the most essential crop nutrients for optimizing grain yields. Traditional uniform N applications, in most cases, result in over- and underapplication of N in various parts of the field due to in-field spatial variability (Frasier et al., 1999; Khosla et al., 1999; Thrikawala et al., 1999). Therefore, maximum net returns may not be achievable with uniform N applications (Prato and Kang, 1998). The ability to variably apply optimum levels of N fertilizer corresponding to site-specific field conditions has been shown to increase N use efficiency, grain yields, crop quality, and net dollar returns while decreasing nutrient overload (Kitchen et al., 1992; Fiez et al., 1994; Prato and Kang, 1998; Cambouris et al., 1999; Snyder et al., 1999; Thrikawala et al., 1999; Yang et al., 1999; Khosla et al., 2002).

The potential for improved profitability due to variable-rate N application depends on identifying areas in the field where additional N inputs will increase revenue on a scale that is greater than the added costs and/or identifying areas where reducing N inputs will decrease costs on a scale that is greater than potential revenue reduction correlated with lower grain yield (Snyder et al., 1999). Therefore, the economic feasibility of variable-rate N application is focused on whether increases in gross revenue or decreases in N input costs outweigh the added cost of technologies or services needed for variable-rate N application (Ferguson et al., 1999; Thrikawala et al., 1999).

Thrikawala et al. (1999) reported that the profitability of variable-rate N application increased above that of uniform N application as area and in-field soil variability increased. However, additional information and application expenses are involved when managing spatial variability occurring throughout a field. Review of literature suggested that most studies incorporated the information costs (i.e., soil sampling, developing variable-rate application maps) but ignored the additional application and equipment costs needed for variable-rate N application (Swinton and Lowenberg-DeBoer, 1998; Thrikawala et al., 1999).

There are few analyses of revenues, costs, and returns associated with variable-rate applications, and the results of the few existing analyses have not been communicated well to growers interested in practicing variable-rate application of N fertilizer. One approach has been an economic study of returns based on variation in grain yield and N rates using partial budgets (Swinton and Lowenberg-DeBoer, 1998). Other studies have used quadratic functions to quantify corn yield response (Snyder et al., 1997, 1999). Similarly, some studies have used simulation models to calculate grain yields, optimal N rates, revenue gains, costs, and net returns (Fraisier et al., 1999; Paz et al., 1999; Thrikawala et al., 1999).

A common factor in the majority of these above studies is that they use grid soil sampling as the primary strategy on which to base a variable-rate N application. In principle, grid-sampling–based N application seems logical, but economically there are limitations. Grid sampling is labor intensive, time consuming, and must be performed every growing season for N levels in fields

ABBREVIATIONS: GIS, geographic information systems; OM, organic matter; SSMZ, site-specific management zone; SSMZ-CYG, site-specific management zone–constant yield goal; SSMZ-VYG, site-specific management zone–variable yield goal; VRT, variable-rate technology.
subject to variable-rate N fertilization (Gotway et al., 1996; Khosla et al., 1999; Fleming et al., 2001; Nolan et al., 2001; Khosla et al., 2002; Koch and Khosla, 2003). Watkins et al. (1999) reported a $43 ha$$^{-1}$$ lower return in potato (Solanum tuberosum L.) production under variable-rate N application compared with uniform application. In their study, the cost of grid soil sampling outweighed any benefits realized by variable-rate N application. Other studies have likewise shown that the cost of grid soil sampling is significantly higher than conventional composite sampling (Khosla et al., 1999; Thirikawala et al., 1999; Yang et al., 1999; Batte, 2000; Fleming et al., 2001; Khosla et al., 2002).

The profitability potential of variable-rate N management is significantly enhanced if the initial means of preparing prescription application maps are less expensive (Peterson and Wollenhaupt, 1996; Koch and Khosla, 2003). Minimal-cost, yet effective approaches for managing spatial variability are needed. Recent research in precision farming has focused on site-specific management zones (SSMZ) as a means to generate nutrient application maps and improve N management in cropping systems (Fleming et al., 2000, 2001; Luchiari et al., 2001; Khosla et al., 2002). Generally, these studies indicate that SSMZ has the potential to be an effective alternative to grid soil sampling for quantifying and managing spatial variability. However, lacking is an economic analyses of SSMZ compared with traditional uniform N management.

No studies have been reported in the western Great Plains region demonstrating the economic feasibility of variable-rate N application utilizing SSMZ. An on-farm, enterprise-based field study was conducted in Colorado to assess the economic feasibility of variable-rate N application utilizing SSMZ. Specific objectives were to: (i) evaluate the economics of four N management strategies, (ii) assess net-return sensitivity of each N management strategy as influenced by changes in grain yield and commodity prices, and (iii) analyze the N management strategies under farmer vs. custom-applied scenarios.

**MATERIALS AND METHODS**

**Field Experiment**

On-farm studies were conducted over three site-years on two continuous corn cropping system fields in northeastern Colorado during the 2000 and 2001 growing seasons. Site-Years I and II were located on a 18.5-ha furrow-irrigated field during 2000 and 2001 in Weld County, CO. Site-Year III represented a 58-ha center-pivot-irrigated field during 2001 in Yuma County, CO (Fig. 1). Study fields had significant variability in soil properties and yield characteristics (Mzuku, 2002; Khosla et al., 2002). Site-Years I and II were planted to Pioneer Brand Hybrid ‘34H98’ on a 50.8-cm row spacing while Site-Year III was planted to Pioneer Brand Hybrid ‘34K77’ on a 76.2-cm row spacing. Soil at the furrow-irrigated site was mapped as Otero sandy loam (coarse-loamy, mixed, mesic Ustic Torriorthents) (Soil Survey Staff, 1982). Soils at the center-pivot-irrigated site were mapped as Albinas loam (fine loamy, mixed, mesic Pachic Argustolls), Ascalon fine sandy loam (fine loamy, mixed, mesic Aridic Argiustolls), and Haxton sandy loam (fine loamy, mixed, Pachic Argiustolls) (Soil Survey Staff, 1981).

Site-specific management zones were delineated on all field sites using the commercially available AgriTrak Professional software (Fleming et al., 1999). This program relies on three geographic information system (GIS) data layers: (i) bare soil aerial imagery on conventionally tilled land, (ii) farmer’s perception of field topography, and (iii) farmer’s past crop and soil management experience. Using these data layers, areas of the field are grouped into management zones of high, medium, and low productivity potential (Fig. 1). Details of this technique are provided in Khosla et al. (2002) and Fleming et al. (1999). Grid soil samples were taken at 0- to 20- and 20- to 61-cm depths on a 0.4-ha square grid using a systematic nonaligned random sampling technique. Residual mineral N was extracted with 2 M KCl. Soil nitrate and organic matter

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**Fig. 1.** (A) The 18.5-ha furrow-irrigated study site (Site-Years I and II) and (B) the 58-ha center-pivot-irrigated study site (Site-Year III), respectively, showing management zones and their corresponding productivity potential. High productivity = dark gray, medium productivity = light gray, and low productivity = white.
(OM) were analyzed by the salicylate and Walkley–Black methods, respectively (Keeney and Nelson, 1982). The analyzed soil data were weighted for the two depths to determine N application rates.

Nitrogen application rates for each N management strategy were calculated using an N recommendation algorithm for irrigated corn (Mortvedt et al., 1996)

\[ N \text{ rate} = 35 + (1.2 \times \text{EY}) - (8 \times \text{soil ppm NO}_3-N) - (0.14 \times \text{EY} \times \text{OM}) - \text{other N credits} \quad [1] \]

where EY is expected yield (which is same as yield goal). Four different N management strategies were evaluated in this study. They were

1. Uniform N application with a constant yield goal.
2. Variable N application based on grid soil sampling with a constant yield goal. The variable-rate N was determined using Eq. [1], as driven by the residual soil NO\(_3\) and OM content obtained at each grid soil-sampling location.
3. Variable N application based on SSMZ using a constant yield goal (SSMZ-CYG). Soil NO\(_3\) and OM levels were determined for each management zone by averaging soil NO\(_3\) and OM values at all grid points that fell within a management zone. Equation [1] was used to determine N-rate for each zone. Soil data were weighted for the two depths to determine was assumed that the variability in soil and crop properties
4. Variable N application based on SSMZ using a variable yield goal (SSMZ-VYG). Soil N rates were determined similar to Strategy no. 3 above, except that a different yield goal was assigned for each management zone.

A constant yield goal of 12.54 Mg ha\(^{-1}\) was the expected yield (EY in Eq. [1]) for the uniform, grid-based, and SSMZ-CYG N management strategies and was determined based on farmer’s knowledge of the field.

Variable yield goals were subjectively determined by consultation with the cooperating farmers based on their experience and previous years of yield maps. For the SSMZ-VYG N management strategy, expected yields were 13.80, 11.91, and 10.03 Mg ha\(^{-1}\) in the high, medium, and low productivity zones, respectively, over all three site-years.

Four experimental strips spanning the length of the field represented the N management strategies and were laid out so they traversed all three management zones (high, medium, and low productivity) at least once. Each N management strategy was replicated four times, using a completely randomized design at the furrow-irrigated study site (Site-Years I and II). The center-pivot–irrigated study site, Site-Year III, had only one experimental strip for each N management strategy. The N fertilizer, urea ammonium nitrate (UAN 32–0–0), was side-dressed 30 to 35 d after emergence between corn vegetative growth stages V6 and V8 (Ritchie et al., 1997). Grain yields were recorded using a Green Star (Deere and Co., Moline, IL) instantaneous yield-monitoring systems. Grain yield data were cleaned using a comprehensive multistep process (Hornung, 2004). Yield maps were created, and grain yields for individual treatment strips and zones were extracted using MapInfo (MapInfo Inc., Troy, NY) GIS software. Mean grain yields in each zone for the various N management strategies were used for economic analysis.

Being a field-scale study, the proportions of management zones (high, medium, and low) in each experimental strip were different. To compare the profitability of each N management strategy, the proportions of management zones were standardized to the proportion of management zones across the entire field. For the furrow-irrigated site (Site-Years I and II), the proportions of high, medium, and low management zones were 0.305, 0.345, and 0.350, respectively, and 0.337, 0.419, and 0.244, respectively, for the center-pivot–irrigated site (Site-Year III) (Fig. 1). For grid-sampling–based N management strategy, it was assumed that the variability in soil and crop properties observed in the experimental strip was representative of the entire field. The mean N rate, grain yields, and net returns for the grid-based N management strategy were the weighted mean of the N rates, grain yield, and net returns, respectively, for the entire experimental strip.

For Site-Year I and II, analysis of variance (ANOVA) was performed on weighted grain yields observed for the four N management strategies to test for significance difference \( (P < 0.05) \). When ANOVA results indicated significant treatment effect, mean separation was performed using LSD (SAS Inst., 2001). For Site-Year III, with no replication, geostatistics was performed on grain yield data to test for spatial dependency using Moran’s I. In the absence of spatial dependency, the grain yield data were subsampled using a sample size of \( n = 40 \) within each management zone (Hornung et al., 2003) and analyzed as for Site-Year I and II.

### Economic Analysis

For this study, each N management strategy was treated as a separate enterprise. The estimated net returns to the land and management were compared to establish the most profitable N management strategy. Crop enterprise budgets were constructed to assess the economics of uniform vs. variable-rate N fertilizer applications over the three site-years. The primary purpose of an enterprise budget is to estimate revenue, costs, and net return for a common base unit (i.e., per hectare), allowing easy comparisons across different enterprises (Kay and Edwards, 1999). Partial budget analysis compares only costs that change from one system to another. We used enterprise budget analysis, which shows all the variable costs associated with a system. Fixed costs were ignored, as they would be with partial budget analysis. However, variable costs that do not change were included to add context to the study.

The first step in economic analysis was to obtain production summaries from the farm cooperators managing each study site. Production summaries included actual management practices, operation schedules, and equipment specifications specific to each study site. Management practices and operation schedules included type and number of tillage operations, type and amount of fertilizer and pesticide applications, seeding rates, irrigation practices, and harvest operations. Equipment specifications included purchase price, salvage value, useful life, annual use, expected life, repairs, implement width, speed of operation, operating efficiency, and coverage per hour of use. Likewise, actual farm-wide use for each piece of equipment was collected from each cooperative to determine equipment’s annual use. Fertilizer, pesticide, seed, and variable-rate N application costs were collected from cooperating farmers and three fertilizer retail dealers in eastern Colorado to obtain average crop input costs. Costs associated with variable-rate N application included grid soil sampling, management zone delineation, custom application, and variable-rate control system cost. Table 1 presents cost of materials and services used in all three site-years.

Utilizing the cost of materials and services, operation schedules, equipment specifications, yield data, N rates, and various technical input, enterprise budgets were constructed using Profit and Loss (PAL) Enterprise Budget software (v1.2) developed by Colorado State University and the USDA (Hoag and Vandenberg, 2003). Enterprise budgets were created for all three site-years for each N management strategy under a farmer and custom-applied scenario. Table 2 illustrates an example of an enterprise budget by operation for the farmer.
applied SSMZ-VYG N management strategy created on the high-productivity management zone for Site-Year III.

Gross revenue or receipts was a product of grain yield and corn price. The price for corn was established to be $111.04, $110.25, and $84.65 Mg⁻¹ for Site-Years I, II, and III, respectively, based on actual prices received by the farm cooperators. Variable or operating costs varied for each management zone, N strategy, and study site (Table 2). Variable machine costs accounted for fuel, oil, lubrication, and repairs for each operation. Material costs included seed, fertilizer, insecticide, herbicide, custom application, trucking expense, irrigation cost, soil sampling, and grain drying. Operating interest accounted for the opportunity cost on money invested in all of these variable inputs. These variable costs were all included in the total operating cost for each operation. Fixed or ownership costs represent those that were constant even with variations in corn production (Table 2). Ownership costs accounted for the interest on investment, machinery depreciation, insurance, general farm overhead, taxes, and land improvements (Kay and Edwards, 1999; Batte, 2000; Doye, 2001). Improvements to land included a center-pivot irrigation system used in the third site-year. No land charge was calculated due to the variety of land types.

Table 2. An example of an enterprise budget by operation for the farmer-applied site-specific management zone–variable yield goal (SSMZ-VYG) N management strategy on the high productivity management zone.

<table>
<thead>
<tr>
<th>Crop:</th>
<th>Corn</th>
<th>Year:</th>
<th>2001</th>
<th>Yield</th>
<th>Units</th>
<th>Price</th>
<th>Gross receipts</th>
</tr>
</thead>
<tbody>
<tr>
<td>Operation type</td>
<td>Name</td>
<td>Date</td>
<td>Machine cost</td>
<td>Material cost</td>
<td>Operating interest</td>
<td>Total operating</td>
<td>Ownership costs</td>
</tr>
<tr>
<td>Other soil sampling</td>
<td>10 Feb. 2001</td>
<td>$0.00</td>
<td>$1.31</td>
<td>$0.10</td>
<td>$4.39</td>
<td>$0.00</td>
<td>$1.39</td>
</tr>
<tr>
<td>Other MZ delineation</td>
<td>15 Feb. 2001</td>
<td>$0.00</td>
<td>$2.47</td>
<td>$0.14</td>
<td>$2.61</td>
<td>$0.00</td>
<td>$2.61</td>
</tr>
<tr>
<td>Tillage</td>
<td>21 Mar. 2001</td>
<td>$5.36</td>
<td>$0.00</td>
<td>$0.46</td>
<td>$3.07</td>
<td>$0.00</td>
<td>$3.07</td>
</tr>
<tr>
<td>Tillage field cultivate</td>
<td>24 Apr. 2001</td>
<td>$3.59</td>
<td>$0.00</td>
<td>$0.35</td>
<td>$3.94</td>
<td>$0.00</td>
<td>$3.94</td>
</tr>
<tr>
<td>Tillage field cultivate</td>
<td>15 May 2001</td>
<td>$3.59</td>
<td>$0.00</td>
<td>$0.35</td>
<td>$3.94</td>
<td>$0.00</td>
<td>$3.94</td>
</tr>
<tr>
<td>Planting</td>
<td>11 May 2001</td>
<td>$12.71</td>
<td>$96.33</td>
<td>$3.64</td>
<td>$110.25</td>
<td>$0.00</td>
<td>$110.25</td>
</tr>
<tr>
<td>Fertilization</td>
<td>10 Jul. 2001</td>
<td>$4.10</td>
<td>$14.10</td>
<td>$0.14</td>
<td>$14.28</td>
<td>$0.00</td>
<td>$14.28</td>
</tr>
<tr>
<td>Pest control</td>
<td>16 Aug. 2001</td>
<td>$0.00</td>
<td>$16.80</td>
<td>$0.12</td>
<td>$16.92</td>
<td>$0.00</td>
<td>$16.92</td>
</tr>
<tr>
<td>Irrigation</td>
<td>10 Sept. 2001</td>
<td>$14.60</td>
<td>$9.20</td>
<td>$0.00</td>
<td>$23.80</td>
<td>$45.10</td>
<td>$68.90</td>
</tr>
<tr>
<td>Harvest</td>
<td>10 Sept. 2001</td>
<td>$0.00</td>
<td>$46.02</td>
<td>$0.00</td>
<td>$46.02</td>
<td>$0.00</td>
<td>$46.02</td>
</tr>
<tr>
<td>Total per hectare</td>
<td></td>
<td>$47.69</td>
<td>$450.12</td>
<td>$9.03</td>
<td>$506.85</td>
<td>$105.24</td>
<td>$612.09</td>
</tr>
</tbody>
</table>

Other ownership costs:
- General farm overhead: $24.70
- Real estate taxes: $24.70
- Improvements: $180.48

Total other ownership costs: $229.88

NET RETURN TO LAND AND MANAGEMENT (ha⁻¹): $78.41
values and ownership scenarios. A farm manager would need to include the land charge as a fixed cost to determine overall profitability. The computed net returns to land and management, however, provide an easy comparison among N management strategies.

When considering the variable-rate N management strategies, the costs associated with variable-rate N management were both fixed and variable (Batte, 2000). Fixed costs accounted for the interest on investment, depreciation, etc., of the GPS receiver, on-board computer, software, data storage card, variable-rate control system, and variable-rate applicator (tractor and cultivators). These were fixed costs amortized over a useful life of 10 yr and spread over 486 and 850 ha of corn grown on the furrow-irrigated (Site-Years I and II) and center-pivot-irrigated (Site-Year III) farms, respectively. There was also a cost associated with speed reduction to variably apply N fertilizer resulting in less coverage per hour. Speed reduction is required to minimize lag time associated with frequent changes in variable N application rates. These are fixed costs that farmers would incur practicing variable-rate N application (farmer-applied scenario). However, farmers may choose to custom-hire the variable-rate N application instead of owning the variable-rate equipment (custom-applied scenario). For this scenario, the cost associated with the VRT equipment is recovered by the custom service as a higher application charge per hectare to the farmer. The custom application cost was variable and appeared in the material costs.

Grid soil sampling was also a variable cost that included labor, sample analysis, and generation of a digital application map. Conversely, management zone delineation was a fixed cost that included the cost of aerial imagery, farmer and agronomist consultation of topography and past management experiences, and generation of a digital application map. Management zone delineation was considered a durable investment, and the cost was amortized over a useful life of 5 yr (Batte, 2000; Fleming et al., 2000, 2001; Heermann et al., 2002; Khovala et al., 2002; B. Gibson, personal communication, 2002; D. Slinger, personal communication, 2002). Composite soil sampling for each zone was a separate charge and considered to be a variable cost. The cost of a yield-monitoring system was assumed to be a fixed cost as yield monitors are now coming as standard equipment for most brand names. For all N management strategies, yield monitor was added to the combine purchase price whether or not the farmer practiced variable-rate N application.

Net returns for each management zone (high, medium, and low) within each N management strategy were computed by subtracting total operating costs and total ownership costs from gross revenue. Weighted mean net returns were a function of management zone proportion across the entire field and should be interpreted as returns to land and management. Weighted mean net returns were used to compare economic differences for N management strategies, observe trends (i.e., in net returns) between each site-year, and establish the most profitable N management strategy. Additional returns due to variable-rate N management were calculated as the difference between variable and uniform N management. A sensitivity analysis of net returns was performed for a broad range of grain yield and commodity price scenarios (Janosky et al., 2002). Simulated grain yields fluctuated incrementally from 9.4 to 13.8 Mg ha$^{-1}$ while corn price fluctuated incrementally from $68.95 to $118.20 Mg$^{-1}$.

### RESULTS AND DISCUSSION

#### Nitrogen Application and Grain Yields

The weighted average amount of N applied for all N management strategies and site-years ranged from 55 to 199 kg ha$^{-1}$ (Table 3). The amount of N applied was the lowest under the SSMZ-VYG N management strategy. Comparing variable-rate against the uniform N management strategy, the grid-based N management strategy had higher N applications by 3, 1, and 30% in Site-Years I, II, and III, respectively. This is in contrast to the findings reported by Snyder et al. (1999) where grid-based N application reduced average N applied by 10%. However, their findings were based on differential yield goals for each grid cell. For our study, grid-based N management was based on a constant yield goal for all grid cells. The SSMZ-CYG N management strategy had higher N applications by 8 and 1% in Site-Years I and II, respectively, and lower N application by 37% in Site-Year III. The SSMZ-VYG N management strategy had lower N applications by 14, 6, and 46% in Site-Years I, II, and III, respectively, than the uniform N management strategy. Savings in N fertilizer under different management strategies will positively influence net returns as long as yields are not impacted negatively.

Weighted mean grain yields across all N management

<table>
<thead>
<tr>
<th>Site-Year I</th>
<th>uniform uniform N rate</th>
<th>184 $^d$</th>
<th>184 $^d$</th>
<th>9.9 $^b$</th>
<th>228.30</th>
<th>233.26</th>
</tr>
</thead>
<tbody>
<tr>
<td>grid-based</td>
<td>variable N rate</td>
<td>132–222</td>
<td>190</td>
<td>9.1</td>
<td>106.06</td>
<td>112.88</td>
</tr>
<tr>
<td>SSMZ-CYG</td>
<td>variable N rate</td>
<td>187–210</td>
<td>199</td>
<td>10.0 $^b$</td>
<td>220.90</td>
<td>227.71</td>
</tr>
<tr>
<td>SSMZ-VYG</td>
<td>variable N rate</td>
<td>137–184</td>
<td>159</td>
<td>10.1 $^a$</td>
<td>253.90</td>
<td>260.71</td>
</tr>
<tr>
<td>Site-Year II</td>
<td>uniform uniform N rate</td>
<td>177 $^d$</td>
<td>177</td>
<td>11.1 ab</td>
<td>352.78</td>
<td>357.72</td>
</tr>
<tr>
<td>grid-based</td>
<td>variable N rate</td>
<td>132–182</td>
<td>179</td>
<td>11.5 a</td>
<td>363.48</td>
<td>370.31</td>
</tr>
<tr>
<td>SSMZ-CYG</td>
<td>variable N rate</td>
<td>167–188</td>
<td>179</td>
<td>11.0 b</td>
<td>332.25</td>
<td>330.06</td>
</tr>
<tr>
<td>SSMZ-VYG</td>
<td>variable N rate</td>
<td>138–188</td>
<td>166</td>
<td>11.4 a</td>
<td>389.25</td>
<td>396.07</td>
</tr>
<tr>
<td>Site-Year III</td>
<td>uniform uniform N rate</td>
<td>102 $^d$</td>
<td>102</td>
<td>10.9 a</td>
<td>72.90</td>
<td>78.89</td>
</tr>
<tr>
<td>grid-based</td>
<td>variable N rate</td>
<td>109–149</td>
<td>133</td>
<td>10.8 a</td>
<td>38.45</td>
<td>44.99</td>
</tr>
<tr>
<td>SSMZ-CYG</td>
<td>variable N rate</td>
<td>68–66</td>
<td>64</td>
<td>11.8 a</td>
<td>105.79</td>
<td>112.12</td>
</tr>
<tr>
<td>SSMZ-VYG</td>
<td>variable N rate</td>
<td>15–88</td>
<td>55</td>
<td>10.8 a</td>
<td>100.38</td>
<td>106.87</td>
</tr>
</tbody>
</table>

$^a$ The SSMZ-CYG and SSMZ-VYG variable-rate N management strategies were based upon site-specific management zones using a constant and variable yield goal, respectively.

$^b$ SSMZ and grid-based weighted N rates were based upon proportions of management zones and grid cells, respectively.

$^c$ Yield for the grid-based strategy was an average yield for the entire treatment strip. Yield for the uniform and SSMZ strategies were weighted mean yields based upon proportions of management zones. Values followed by the same letters are not significantly different at $P < 0.05$.

$^d$ Net returns should be interpreted as returns to land and management.
strategies and site-years varied from 9.9 to 11.5 Mg ha\(^{-1}\) (Table 3). When examining mean grain yields for each site year, the SSMZ-VYG N management strategy resulted in grain yield equal to or higher than uniform and grid-based N management strategies (\(P < 0.05\)). However, the weighted mean N rate applied for the SSMZ-VYG N management strategy was significantly lower than the other N management strategies (Table 3). Such a finding reinforces the principle advantage of variable-rate N management as reported by Yang et al. (1999), Fleming et al. (2000, 2001), and Khosla et al. (2002).

**Total Costs**

Overall, the lowest total cost of production was $788.37 ha\(^{-1}\) for the custom-applied SSMZ-VYG N management strategy (low zone) while the highest total cost was $907.52 ha\(^{-1}\) for the farmer-applied grid-based N management strategy. Several key findings were observed when comparing total cost of production between N management strategies. The low productivity zone in the SSMZ-VYG N management strategy had the lowest expense ($788.37 to $865.15 ha\(^{-1}\)) compared with that of other management zones and was consistent among site-years. This can be attributed to the optimum N rate application (significantly less than the other N management strategies) on low productivity zones for the SSMZ-VYG N management strategy. The grid-based N management strategy was found to be the most expensive form of variable-rate N management attributed to relatively higher N rates (two out of three site-years) and grid soil-sampling costs associated with the strategy ($24.70 ha\(^{-1}\)) (Table 3). Comparing the two N application scenarios (i.e., farmer-applied and custom-applied), farmer-applied variable-rate N application was found to be less profitable due to costs associated with the farmer owning and operating the variable-rate applicator (i.e., DGPS receiver, variable-rate controller, tractor, cultivator, etc.). This finding contradicts the general perception that farmer-owned operations are either equal or less expensive than custom services (Gutierrez and Dalsted, 1992; R. Johnson, farmer, personal communication, 2002). However, there was a $5.56 ha\(^{-1}\) cost increase for a custom service to variably apply N vs. uniformly applying N (Table 1). Interestingly, there was only a $2.92 to $4.80 ha\(^{-1}\) increase for the farmer to invest in the VRT equipment (i.e., variable-rate control system and software) needed to variably apply N. This study revealed that total costs associated with the variable-rate fertilizer applicator (i.e., tractor depreciation, interest, coverage reduction, fuel, etc.), not the VRT equipment, resulted in higher cost for farmer-applied variable-rate N application. More specifically, purchase prices for the tractors used in this study ($113 000 and $85 000) were the main influence for high ownership (fixed) costs associated with the variable-rate N fertilizer applicator. High total costs associated with the farm equipment used in this study will influence net returns for the farmer-applied scenario.

The size of the farm was also found to be an important factor governing costs associated with VRT equipment. In this study, total farm sizes were 486 ha for Site-Years I and II and 850 ha for Site-Year III. Larger farm size (850 ha) allowed fixed costs associated with VRT equipment to be spread over a larger area, thereby decreasing the fixed expense of VRT equipment from $4.28 to $2.44 ha\(^{-1}\) for the farmer-applied scenario. This decline in cost as farm size increased is known as economics of scale (Batte, 2000). Such economics may justify ownership of durable capital investments (i.e., VRT equipment) and allow adoption of this technology on larger farms. Similar results regarding the relationship between farm size and fixed costs have been reported (Thrikawala et al., 1999; Batte, 2000).

**Mean Net Returns**

Weighted mean net returns based on the farmer’s actual corn price across all N management strategies and site-years ranged from $38.45 to $396.07 ha\(^{-1}\) (Table 3). Comparing variable and uniform N management strategies at the farmer’s corn price, the SSMZ-VYG N management strategy produced the highest net return per hectare under both farmer-applied and custom-applied scenarios in Site-Years I and II. Additional returns due to variable N management using the SSMZ-VYG N management strategy over uniform N application ranged from $25.60 to $38.35 ha\(^{-1}\) in Site-Years I and II. These results support the findings of Prato and Kang (1998) that variable-rate N management is more profitable than uniform N management under continuous corn cropping systems. Factors that contributed toward additional returns for this strategy were grain yield, N fertilizer savings, and recovery of variable-rate application expenses (Tables 1 and 3).

For Site-Year III, the SSMZ-CYG and SSMZ-VYG N management strategies showed no difference (\(P < 0.05\)) with respect to grain yield. However, the SSMZ-CYG strategy produced the highest net return per hectare under both N application scenarios (i.e., farmer-applied and custom-applied) (Table 3). Additional returns due to variable N management using the SSMZ-VYG N management strategy over uniform application were $32.89 and $33.43 ha\(^{-1}\) for the farmer- and custom-applied scenarios, respectively (Table 3). The SSMZ-VYG N management strategy resulted in additional returns to variable N management over uniform N application of $27.48 and $27.98 ha\(^{-1}\) for the farmer- and custom-applied scenarios, respectively. The profitability of the SSMZ-CYG and SSMZ-VYG N management strategies is attributed to significant N fertilizer savings (37–46%) and recovery of variable-rate N application expenses (Tables 1 and 3). Increased N fertilizer application (30%), grid-sampling costs ($24.71 ha\(^{-1}\)), and additional variable-rate N application costs for the grid-based N management strategy resulted in the lowest net return among all N management strategies. This corresponds to previous economic feasibility studies reported by Thrikawala et al. (1999) and Watkins et al. (1999).

**Sensitivity Analysis**

Market prices and grain yields fluctuate extensively over time, and negative net returns are not uncommon.
in grain production when government payments, commodity premiums, and price hedging are excluded from economic analysis (Janosky et al., 2002). For example, market prices obtained by the cooperating farmers ranged from $84.65 to $110.44 Mg⁻¹ while the 5-yr average price was $83.48 Mg⁻¹. Likewise, irrigated corn yields in this region vary from year to year. To illustrate the effect of various corn price and grain yield combinations on net return, a sensitivity analysis was performed to show net-return sensitivity for the four N management strategies in Site-Year I (Table 4). Results for the SSMZ-VYG N management strategy, the most profitable strategy in Site-Year I, are discussed to illustrate the effects of various price and yield combinations.

The SSMZ-VYG strategy’s mean grain yield was 10.1 Mg ha⁻¹. When the farmer’s price of $110.44 Mg⁻¹ was realized, net returns equaled $255.35 ha⁻¹. This return was $278.86 ha⁻¹ more than had the farmer only realized the 5-yr average price of $83.48 Mg⁻¹. Prices of $88.65 ha⁻¹ or more are shown to generate positive net returns for all yields of 10.03 Mg ha⁻¹ or more (Table 4). Such an observation suggests that market price increase in the future, the application of SSMZ and VRT for N management would become more profitable. Similar net-return sensitivity was observed in Site-Years II and III as the farmer’s received a $110.25 and $84.65 Mg⁻¹ price for corn, respectively. When examining the effects of various corn price and grain yield combinations over all site-years, the SSMZ-VYG N management strategy was consistently more profitable than uniform N management.

**Farmer- and Custom-Applied Scenarios**

A few key points should be discussed for farmer-applied vs. custom-applied variable-rate N applications. In this study, net returns were slightly lower ($4.94 to $6.83 ha⁻¹) for the farmer-applied scenario (Table 3). However, variable-rate application of N fertilizer is not necessarily a separate farm operation in irrigated cropping systems as we considered it. It is usually coupled with an existing cultivation operation ($15.94 to $16.60 ha⁻¹) where N fertilizer can be sidedressed (L. Baucke, personal communication, 2002; R. Johnson, personal communication, 2002). In this case, the only additional cost to farmer-applied variable-rate N application would be associated with the VRT equipment ($2.92 to $4.80 ha⁻¹) and any efficiency reductions related to variable-rate N application ($2.84 to $3.28 ha⁻¹). If a decision was made to variably apply N using a custom service, there would be a custom charge (approx. $15.44 ha⁻¹) plus the fixed and variable costs (i.e., depreciation, interest, fuel, etc.) on the cultivation operation ($15.94 to $16.60 ha⁻¹). Therefore, combining VRT equipment with an existing cultivation or uniform N fertilizer application ($22.80 to $23.58 ha⁻¹) would be more profitable than hiring a custom service to variably apply N fertilizer ($31.38 to $32.04 ha⁻¹). Moreover, economics of scale may justify ownership of VRT equipment and allow adoption of this advanced technology (Thirikawala et al., 1999; Batte, 2000). Timeliness and quality of application may also deter hiring a custom service (Dalsted and Gutierrez, 1992). However, there is a fixed cost associated with management of VRT. Further, there is typically a considerable learning process necessary for efficient and successful use of VRT. Development of such knowledge may be substantial, and some farmers may find it more feasible to hire a custom service to manage the advanced technology needed for variable-rate N application. Similar studies have recognized this cost associated with management of VRT (Snyder et al., 1999; Batte, 2000).

**Table 4. Net return sensitivity corresponding to increases and decreases in corn price and grain yield for the farmer-applied N management strategy in Site-Year 1.**

<table>
<thead>
<tr>
<th>Yield (Mg ha⁻¹)</th>
<th>Corn price (price for corn, respectively)</th>
<th>Net return, $ ha⁻¹</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Uniform</td>
<td>Grid-based</td>
</tr>
<tr>
<td>9.4</td>
<td>$68.95</td>
<td>$78.80</td>
</tr>
<tr>
<td>10.03</td>
<td>$88.65</td>
<td>$98.50</td>
</tr>
<tr>
<td>10.66</td>
<td>$108.35</td>
<td>$118.20</td>
</tr>
<tr>
<td>11.29</td>
<td>$110.21</td>
<td>$112.18</td>
</tr>
<tr>
<td>11.92</td>
<td>$125.36</td>
<td>$127.24</td>
</tr>
<tr>
<td>12.55</td>
<td>$134.95</td>
<td>$136.71</td>
</tr>
<tr>
<td>13.18</td>
<td>$147.81</td>
<td>$149.57</td>
</tr>
<tr>
<td>13.81</td>
<td>$157.86</td>
<td>$160.32</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Site-specific management zone–constant yield goal</th>
<th>Farmer’s price: $111.04 Mg⁻¹; 5-yr average: $83.48 Mg⁻¹</th>
</tr>
</thead>
<tbody>
<tr>
<td>9.4</td>
<td>$234.99</td>
</tr>
<tr>
<td>10.03</td>
<td>$296.70</td>
</tr>
<tr>
<td>10.66</td>
<td>$335.45</td>
</tr>
<tr>
<td>11.29</td>
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<tr>
<td>11.92</td>
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<tr>
<td>12.55</td>
<td>$518.77</td>
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<td>$586.54</td>
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<tr>
<td>13.81</td>
<td>$654.30</td>
</tr>
</tbody>
</table>

For N management would become more profitable. Similar net-return sensitivity was observed in Site-Years II and III as the farmer’s received a $110.25 and $84.65 Mg⁻¹ price for corn, respectively. When examining the effects of various corn price and grain yield combinations over all site-years, the SSMZ-VYG N management strategy was consistently more profitable than uniform N management.
from $18.21 to $29.57 ha\(^{-1}\) over the uniform N management strategy in all three site-years. The SSMZ-VYG N management strategy was also significantly more cost effective than the grid-based N management strategy in all three site-years. The variable-rate N applications based on grid soil sampling were economically unfeasible due to costs associated with grid soil sampling and increased application of N fertilizer. However, future studies that incorporate variable yield goal for each grid cell as a part of grid-based N management strategy may justify economic feasibility of using this strategy. The SSMZ-VYG N management strategy was also found to be more profitable than site-specific management zones based on a constant yield goal. Combining two separate field operations (VRT and cultivation) was found to be more economically feasible than hiring a custom service to variably apply N fertilizer. Moreover, economics of scale may justify ownership of VRT equipment and allow adoption of this advanced technology for many farming operations. Benefits and costs associated with farmer- and custom-applied scenarios should be assessed on a farm-specific basis to establish the most profitable variable-rate N application scenario. Results of this study confirm that variable-rate N application utilizing SSMZs improves farm profitability and is an economically feasible venture compared with traditional uniform N management.

Although this study measured the economic benefits related to alternative N management strategies, associated studies are revealing the environmental advantages of utilizing SSMZ and VRT (Batte, 2000; Khosla et al., 2002; Stafford and Werner, 2003). These studies have suggested that decreasing N fertilizer using VRT may reduce environmental pollution resulting from agriculture. Adapting SSMZ and VRT has the potential to create a more environmentally friendly, profitable, and sustainable agriculture.

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REFERENCES


Stafford and Werner, 2003). These studies have June 1996. ASA, CSSA, and SSSA, Madison, WI.


Khosla, R., K. Fleming, J.A. Delagado, T.M. Shaver, and D.G. Westfall. 2002. Use of site-specific management zones to improve nitro-


