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A synthesis of multi-disciplinary research in precision agriculture: site-specific management zones in the semi-arid western Great Plains of the USA

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Abstract Researchers from Colorado State University, in collaboration with scientists from the United States Department of Agriculture (USDA), initiated a long-term multi-disciplinary study in precision agriculture in 1997. Site-specific management zones (SSMZ) were investigated as a means of improving nitrogen management in irrigated maize cropping systems. The objective was to develop precise nutrient management strategies for semi-arid irrigated cropping systems. This study was conducted in five fields in northeastern Colorado, USA. Two techniques for delineating management zones were developed and compared: SSMZ and yield-based management zones (YBMZ). Nitrogen uptake and grain yield differences among SSMZs were compared as were soil properties. Both management zone techniques were used to divide fields into smaller units that were different with regard to productivity potential (e.g., high zones had high productivity potential while low zones had low productivity potential). Economic analysis was also performed. Based on grain yield productivity, the SSMZs performed better than the YBMZ technique in most cases. Grain yield and N uptake between the low and high productivity management zones were statistically different for most site-years and N fertilizer rates ($p < 0.05$). Soil properties helped to explain the productivity potential of the management zones. The low SSMZ was markedly different from the high SSMZ based on bulk density, organic carbon, sand, silt, porosity and soil moisture. Net returns ranged from 188 to 679

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USD ha^{-1}. In two out of three site-years the variable yield goal strategy resulted in the largest net returns. In this study, the SSMZ approach delineates areas of different productivity accurately across the agricultural fields. The SSMZs are different with regard to soil properties as well as grain yield and N uptake. Site-specific management zones are an inexpensive and pragmatic approach to precise N management in irrigated maize.

Keywords Management zones · Nitrogen fertilizer · Variable-rate · Net returns · Nitrogen-use efficiency

Introduction

Project background

In 1997 scientists from Colorado State University (CSU), in collaboration with researchers from the United States Department of Agriculture's Agricultural Research Service (USDA-ARS), initiated a long-term research project to investigate how precision agriculture (PA) could be used across different cropping systems throughout the semi-arid Western Great Plains region of the United States. From the beginning of the project, study sites were located on commercially-operated, irrigated, production agricultural fields throughout eastern Colorado, USA. In addition to providing scientists with study areas within their fields, cooperating producers were also involved as stakeholders and advisors throughout the project; their input helped to guide and ultimately shape the overall project. During the first two years of the project (1997–1999) the primary objective was to record baseline data from the study sites to understand the spatial and temporal variation of soil properties and crop yields better across the fields of interest. By the end of the initial phase of the project, it was evident that there was more variation (both spatial and temporal) across the fields than had been anticipated originally. Nevertheless, this discovery presented an opportunity to develop PA strategies to manage spatial and temporal variation better. Following meetings with cooperating producers and other stakeholders, these questions were raised: (i) can spatial variation of soil fertility levels and soil properties be characterized across production agriculture fields without costly intensive grid sampling of the soil? (ii) can grain yield and the efficiency of nutrient use be improved by variable-rate application of fertilizers? (iii) does the crop remove nutrients differentially across the field? and (iv) is PA economically viable?

Soil throughout the Western Great Plains region of the USA generally has adequate levels of phosphorous and potassium, however; nitrogen is often limiting, particularly in irrigated cropping systems. Therefore, development of techniques that could be used for N fertilizer management became a primary focus of the project following the initial phase of data collection. At that point in time (i.e., 1999), management zone work in the semi-arid Western Great Plains of the USA was ground breaking. Scientists from CSU and the ARS developed and assessed several innovative techniques to delineate management zones. The techniques developed during the early stages of this project included the use of yield monitor data, spatial statistical modeling of soil properties, apparent electrical conductivity, remotely sensed imagery, and topography, as well as various combinations of these data (e.g., Fleming et al. 2000; Fleming et al. 2004; Khosla et al. 2002; Hornung et al. 2006).

The overall goal of this paper was to synthesize the results of a long-term interdisciplinary research project conducted by researchers from CSU and USDA-ARS to understand the role of management zones and precision agriculture in irrigated maize cropping systems better.

Therefore, the overall objective of this project was to develop strategies for precise nutrient management for semi-arid irrigated cropping systems. The specific objectives were: (i) to develop and compare the accuracies of two management zone strategies (site-specific management zone vs. yield monitor data-based management zone), (ii) to quantify and compare N uptake and grain yield across SSMZs, (iii) to ascertain the soil properties that exert the strongest influence on SSMZs, (iv) to compare net returns achieved by variable-rate N management strategies.

Theory

Characterizing spatial variation

Grid-based soil sampling was one of the first methods used to characterize spatial variation of soil fertility levels across agricultural fields. Although such soil sampling has been used widely to develop variable-rate application (VRA) prescription maps, it has been shown to be prohibitively costly because of both the costs of sampling and the associated laboratory analyses. Reducing the number of soil samples collected per unit area reduces both the cost and accuracy of VRA maps from the grid-based sample. Because of the above limitations, alternatives to grid-based soil sampling need to be considered (Gotway et al. 1996; Khosla and Alley 1999).

Efforts to characterize spatial variation with little to no soil sampling have led to the development of management zones. These zones should be regions within a field that have similar yield-limiting factors (Doerge 1999). Although there are several techniques to delineate management zones, most rely on little to no soil sampling, and so they have the potential to be more feasible economically than sampling on a grid. Regardless of the technique used, once a field has been divided into management zones agricultural inputs are applied variably to meet the yield-limiting factors inherent to each zone.

Several methods of delineating management zones have capitalized on one or more of the soil forming factors to characterize soil variation. For example, USDA county soil surveys have been studied to create N management zones. Franzen et al. (2002), however, found that standard soil surveys (i.e., 1:15 840 and 1:24 000-scale) were not adequate for developing N management zones. Field topography has also been used to identify management zones. Field topography in combination with ancillary data such as soil organic matter, cation exchange capacity and land-form have been shown to relate strongly to grain yield (Kravenchenko and Bullock 2000; Nolan et al. 2000).

Other methods of management zone delineation have used remote sensing technologies to characterize within-field spatial variation of soil properties. Apparent electrical conductivity (EC_a) has been shown to be strongly related to soil texture, moisture content, and $CaCO_3$ (Johnson et al. 2001; Inman et al. 2002). In spite of the strong relationship between soil EC_a and some soil properties, management zones based on soil EC_a have been poorly correlated with grain yields (Johnson et al. 2003). Spectral reflectance has also been shown to be strongly correlated with soil organic matter, moisture content, and texture (Bowers and Hanks 1965; Coleman and Montgomery 1987; Coleman and Tadesse 1995; Lobell and Asner 2002; Ray et al. 2004). Zones developed from such data alone have been markedly different with regard to grain yield, but not to nutrient content (Yang et al. 1998).

Data from yield monitoring equipment have also been investigated as a means of generating management zones. However, such zones have not characterized spatial variation in the soil accurately. Spatial and temporal yield patterns are very variable and inconsistent between growing seasons (Kitchen et al. 1995; Lamb et al. 1996; Colvin et al. 1997; Stafford et al. 1998). Although yield monitor data alone might be unsuitable for the delineation of management zones, they are a valuable source of ancillary information, especially when compiled over several growing seasons (Stafford et al. 1998).

Overall, the most promising techniques to delineate management zones use multiple sources of data or layers for the purpose. For example, elevation, soil EC_a, and slope have been used to create successful management zones (Fraisse et al. 1999; Fridgen et al. 2000). Likewise, soil EC_a together with soil color and topography has been shown to be strongly correlated with the spatial variation of maize (*Zea Mays* L.) grain yield (Luchiari et al. 2000). Fleming et al. (2000) proposed a subjective management zone technique that used bare-soil color in combination with the producer's input to create management zones for irrigated maize fields. Studies have shown that in irrigated maize cropping systems, the technique of Fleming et al. (2000) effectively delineates areas of differential crop productivity. Although several techniques to delineate management zones have been reported in the literature there are few studies that compare them in terms of the accuracy with which the spatial variation of grain yield and nutrient uptake is characterized.

Grain yield and nitrogen use efficiency

Managing nitrogen (N) fertilizer to maximize crop yields without negative environmental impacts is challenging. Nitrogen applied in excess of the crop's needs is susceptible to losses from the soil-crop system. Strategies that strive to improve the efficiency of N use would benefit growers by increasing farm profits and reducing the environmental effects associated with excessive fertilizer use. Increasing the efficient use of N is becoming more important with the increases in N fertilizer costs.

Agricultural N fertilizer application rates in many regions of the United States are determined using N-rate algorithms that are based on field average productivity. Most of these algorithms were developed on the basis that they would be used by producers within large geographical areas (i.e., an entire state or region). However, such N management strategies do take into account the inherent variability of yield limiting factors within the field and so they can perpetuate the poor overall efficiency of N use observed for many crops, in particular cereals. Many rural watersheds in the central United States have groundwater nitrate levels that exceed the U.S. Environmental Protection Agency's benchmark of 10 mg l^{-1} (Jaynes et al. 1999; Weed and Kanwar 1996; Randall et al. 1997). The development of N management strategies that use innovative techniques, such as remote sensing, global positioning systems, and variable-rate application to account for within-field variation might help to increase the efficiency of N use, reduce environmental impact and improve overall product quality at the farm level (Delgado et al. 2001).

Equipment that allows variable-rate application of fertilizers to manage inherent soil variation has been one of the most important agricultural advancements over the last two decades. Variable-rate application of N fertilizers has the potential to reduce the deleterious effects of nitrate leaching and to increase the overall efficiency of N use (Mulla and Bhatti 1997; Khosla and Alley 1999; Khosla et al. 2002; Dinnes et al. 2002; Mamo et al. 2003). Before variable-rate application of fertilizer can be implemented, the within-field variation must be quantified accurately and mapped (Sawyer 1994; Ferguson et al. 1996). Ideally, to be effective PA strategies should have the potential to be adopted widely by

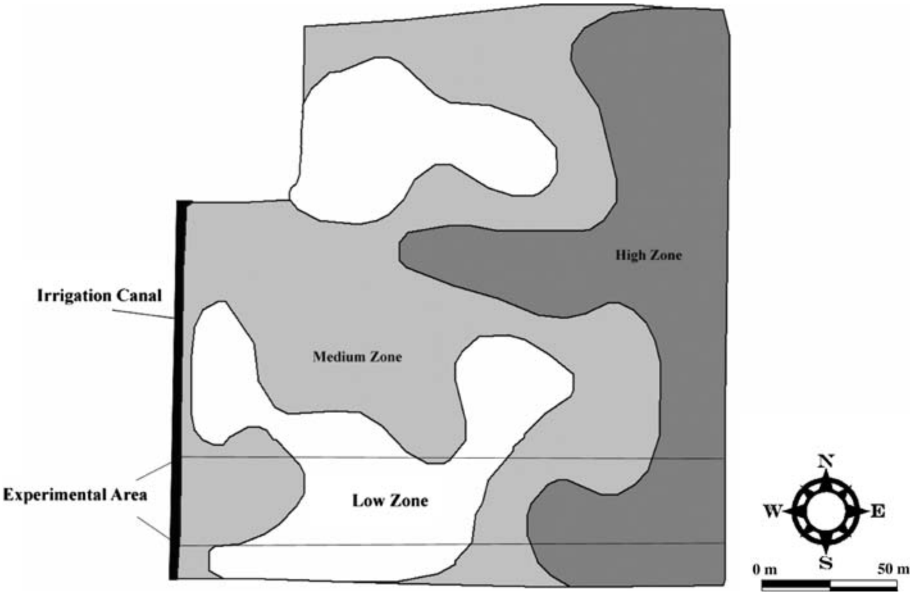

Fig. 1 Example of one of the five irrigated production maize fields used for this study. Location of the experimental area, irrigation canal, and site-specific management zones (white = low zone, grey = medium zone, and dark grey = high zone)

producers. Strategies that are difficult and cumbersome are unlikely to be adopted, regardless of their accuracy.

Materials and methods

This study was conducted on fields that are characteristic in size, management, and soil properties of the irrigated continuous corn cropping systems that are ubiquitous in the Western Great Plains region of the USA. Overall, a total of 15 site-years were used in this study. For this study, site-year is defined as one growing season on one field.

Objective 1: comparison of two management zone techniques

Site-specific management zones (SSMZ) and yield-based management zones (YBMZ) were compared using three criteria described below. Prior to planting each growing season, fields were classified into areas of high, medium, and low productivity potential (Fig. 1) using both SSMZ and YBMZ techniques.

The SSMZ approach in this study uses AgriTrak Professional™[1] software to delineate management zones (Fleming et al. 2000). Three data layers are put into the program: (a) panchromatic aerial imagery of each field following convention tillage operations; (b) producer's knowledge of the field's topography; and (c) the producer's past crop management experience in the field. Using AgriTrak™ Professional, the cooperating producers examine the aerial imagery and provide input reflecting their knowledge and

[1] Mention of a trade name neither constitutes endorsement of the equipment or products used nor criticism of similar ones not used or mentioned by the authors.

past management experiences with the fields. For example, cooperating producers help to locate and identify areas within the fields that are consistently low or high yielding as well as areas that are upland positions and or areas that are low-lying or drained.

The YBMZ technique used here was developed in collaboration with cooperating producers and was intended to improve the accuracy of the SSMZ technique by including yield monitor data. Five data layers are used for zone delineation: (a) color infra-red bare-soil aerial imagery (red, green, and near infra-red bands), (b) soil organic matter content, (c) soil cation exchange capacity, (d) soil texture (sand, silt, and clay contents); and (e) the yield map from the previous growing season. Details of the steps are provided below:

Color infra-red imagery was acquired for each field by aircraft following conventional tillage operations. Imagery was recorded with a DuncanTech MS 3100 three-band (green, red, near infra-red) digital camera (Redlake MASD Inc., San Diego, CA USA). Imagery was processed in ERDAS Imagine 8.6 (Leica Geosystems GIS & Mapping LLC, Atlanta, GA USA).

Geo-referenced soil samples were taken on a 0.4-ha grid and analyzed for soil organic matter, cation exchange capacity and texture. Interpolated surfaces were created for each soil property by median-polish kriging (Cressie 1993) because they showed strong trend in their variation, and for the yield data by ordinary kriging (Cressie 1993). Both the median-polish and ordinary kriging are interpolation techniques that depend on the spatial dependence between data points. Median polish kriging is described in more detail in Cressie (1993); it is based on the median polish approach for two-way tables to extract a mean surface from spatial data. Ordinary kriging is then used to predict the residual process. Median polish kriging has two advantages over universal kriging for dealing with data with trend: first, the mean component of the model is estimated by the outlier resistant method of median polishing, which gives less biased residuals for estimating the variogram, and second, the latter is not assumed to be known a priori (Cressie 1993). All data layers (i.e., yield maps, soil surfaces and imagery) were re-sampled by cubic convolution and scaled to 10 m for zone delineation. A *k*-means clustering approach (MacQueen 1967) was then used to create three management zones. The resulting zones were ‘smoothed’ using a 7 m $\times$ 7 m moving window; the size of the window was chosen to correspond to the width of the fertilizer machinery used in this study (the application boom used was 7-m wide).

Experimental strips of 24 maize rows that spanned the length of the entire field (i.e., >700 m) were allocated randomly within each field. Treatments were replicated once and were nested within management zones. Nitrogen treatments were made at the six-leaf crop growth stage (V6) using undiluted urea ammonium nitrate 32% (UAN 32) applied with an eight-row cultivator. Nitrogen treatments were based on the N-rate algorithm for irrigated maize provided by the CSU Cooperative Extension Service (Mortvedt et al. 1996). The three N treatments were: (i) the recommended N rate from Mortvedt et al. (1996), (ii) half the recommended N rate, and (iii) a control of 0 kg N ha^{-1}. Recommended N rates ranged from 102 to 202 kg N ha^{-1}. Fields were harvested with a combine equipped with a yield monitor and a differentially-corrected global positioning system.

Management zone techniques were compared using three criteria: (i) crop productivity, (ii) an assessment of accuracy and (iii) subjective classification. Criterion one was based on comparing the grain yield production between the two delineation techniques; comparisons were made for grain yield produced in each zone for both techniques. For example, the grain yield from the high zone delineated by SSMZ was compared to the grain yield from the high zone delineated by YBMZ.

Assessment of accuracy involved the use of an error matrix to compare classifications. The *k*-means clustering was used to group the grain yield into three clusters of high, medium, and low grain yield. Yield clusters were compared to the management zones using an error matrix (Campbell 2002). Error matrices were used to compare quantitatively two areal classifications (i.e., the management zone maps and grain yield clusters) by a point-to-point comparison. The percentage areal agreement and Kappa statistics were calculated from the error matrix to assess the agreement between the classifications. The percentage areal agreement is the percentage of points compared that share a common classification. This measure, however, can be biased by the number of classes in the comparison. The Kappa statistic, on the other hand, provides a rigorous measure of how well the classifications agree compared to a 'chance' agreement; more details on the kappa can be found in Campbell (2002).

The subjective classification was similar to criterion 2, except the yield classes were chosen subjectively after consultation with cooperating producers. These classes were: low yield class = <9 Mg ha^{-1}; medium yield class = $9-12$ Mg ha^{-1}; high yield class >12 Mg ha^{-1}. They were chosen by cooperating producers to reflect their experience with the region's below average, average, and above average irrigated maize grain yields. Yield classes were compared to the management zones using an error matrix as described above.

Objective 2: N uptake and grain yield across SSMZs

Although two management zone techniques were developed during the early phase of the project, only the SSMZ technique was used throughout the project. Based on field results and producer feed-back, the SSMZ technique was retained to the exclusion of others because of its ease of use and effectiveness. Therefore, throughout the remainder of this study, the objectives will focus on the SSMZ technique only.

Fields were divided into SSMZs and N fertilizer treatments were applied as described in Objective 1. At physiological maturity, randomly selected above-ground biomass samples were collected for analysis. Biomass samples were collected by hand from a 1-m by 0.3-m area. Samples were Air-dried and analyzed for grain yield, moisture, and N content.

Statistical analysis was performed with SPLUS 6.1 and SAS 8.0. Differences in grain yield and N uptake between all SSMZs were analyzed using a fixed-effect, two factor nested analysis of variance (ANOVA). For example, the low zone was compared to both the medium and high zones; this was repeated for all combinations of zones. When ANOVA was significant at $p < 0.05$, mean separation was then performed using LSD (Least Significant Difference) mean separation. In addition to ANOVA and mean separation, zone differences were further analyzed by investigating differences in grain yield response to applied nitrogen fertilizer across the SSMZs. To accomplish this, least squares regression analysis was used to model grain yield response to applied N. For this study, binary indicator variables were assigned to each SSMZ and included as independent variables in the regression analysis (e.g., $X_1 = 1$ if high zone, $X_1 = 0$ otherwise; $X_2 = 1$ if medium zone, $X_2 = 0$ otherwise, etc.). Neter et al. (1996) provide a complete explanation of the use and interpretation of indicator variables in regression modeling.

Objective 3: soil physical properties across SSMZs

Management zones were delineated for each field by the SSMZ technique described above (Fleming et al. 2000). Soil samples were collected from each field before planting using a non-aligned systematic grid; the sampling density was 2.5 samples per hectare. Depending upon the size of the field, the total number of samples per field varied between 30 and 85 samples. Geographic coordinates were recorded for each sampling point with a Trimble Ag 114™ differentially corrected global positioning system unit. Soil samples were taken from the surface at 0–10 cm depth and from the subsurface at the following depth increments: 10–30, 30–60, and 60–90 cm. The bulk density of each soil sample was determined by the method of Donahue et al. (1983). Organic carbon content was determined using Nelson and Sommers (1996). Soil texture was determined by the hydrometer method (Gee and Bauder 1986). Multi-response permutation procedure (MRPP) was used to test for significant differences in soil properties between the SSMZs (Mielke 1991).

Objective 4: economic analysis of SSMZs

Enterprise budgets were created for fields and N management strategies using the Profit and Loss Enterprise Budget software (v.2.0) (Hoag and Vandenberg 2003). Gross revenue was calculated based on prices of $138 (USD) per Mg maize grain, and $0.16 per kg N. Net returns were calculated as the difference between total operating costs (including ownership costs) and gross revenue. Since the size of each management zone within a field was not equal, weighted mean net returns were calculated based on the proportions of management zones across the entire field.

Four N management strategies were evaluated on the basis of economics. The strategies were:

1. Uniform N rate application.
2. VRA-N based on sampling soil on a grid. Soil samples were collected using a 0.4-ha grid and analyzed for soil NO_3 and organic matter (OM). The variable-rate N was determined for each 0.4-ha area using recommendations by Mortvedt et al. (1996).
3. VRA-N rate using a constant yield goal (CYG). Soil NO_3 and OM levels were determined for each management zone, and N rates for each zone were determined using recommendations by Mortvedt et al. (1996). This strategy resulted in the largest N rates being applied to the low management zones.
4. VRA-N rate using a variable yield goal (VYG). Fertilizer N application rates were determined as with the CYG strategy above, except that a different yield goal was assigned to each management zone. This strategy resulted in the largest N rates being applied to the high management zones.

The above strategies were applied to the strips described above. Each strategy was replicated four times and nested within the management zones. Grain was harvested as described in Objective 1. To compare the profitability of each N management strategy, the proportions of management zones were standardized by the proportion of management zones across the entire field.

Results and discussion

Comparison of SSMZ and YBMZ

Grain yield production

Grain yield differences across both SSMZs and YBMZs are given in Table 1. In general, the high and medium zones delineated by SSMZ were as much as 1.88 Mg ha^{-1} higher yielding than the high and medium zones delineated by YBMZ. The techniques to delineate management zones were significantly different with regard to grain yield

Table 1 Selected grain yield differences between site-specific management zones and yield-based management zones across three agricultural fields used in this study

Field	N treatment	Grain yield difference (Mg ha^{-1})[a]		
		Management zone		
		High	Medium	Low
A	Rec.[b]	0.38*	0.13	−0.38
	½ Rec.	0.63*	–	−0.38
	Control	0.50	0.44*	−0.44
B	Rec.	0.13	1.0*	−1.63*
	½ Rec.	0.38	1.25*	0.63
	Control	−1.63	−2.19*	−0.50**
C	Rec.	0.01	0.06	0.31
	½ Rec.	1.88*	–	−0.25*
	Control	0.50*	0.44	−0.44*

Adapted from Hornung et al. (2006)

[a] Grain yield differences were calculated by subtracting the grain yield of the YBMZ zones from the grain yield of the SSMZ zones

[b] Rec. = The recommended N rate as determined by (Mortvedt et. al. 1996)

* Indicates statistical significant at $p \leq 0.05$

** Indicates statistical significant at $p \leq 0.01$

– Indicates no data

production for corresponding management zones in nearly half of the comparisons ($p \leq 0.05$). Low zones delineated by YBMZ were as much as 1.63 Mg ha^{-1} higher yielding than low zones delineated by SSMZ. Based on grain yield productivity, SSMZ performed better than YBMZ in terms of identifying productivity potential. Overall, the SSMZ technique resulted in more accurate high, medium, and low productivity potential zones compared to the YBMZ technique.

Accuracy assessment

Guidelines for the interpretation of the Kappa statistic are given in Table 2 (Landis and Koch 1977). The SSMZ technique had a larger percentage areal agreement in nearly 70% of comparisons in the fields. With the guidelines from Table 2, both SSMZ and YBMZ have only a weak relation with the yield clusters. These results suggest that neither technique completely characterizes the spatial variation in grain yield productivity potential across the fields used in this study. Although inconclusive, the Kappa statistics were larger for SSMZ across all site years than for YBMZ. These results suggest that SSMZ relates more strongly to the spatial patterns of grain yield.

Subjective classification

The subjective classification compared subjectively determined yield classes to management zones using percentage areal agreement and Kappa statistics. Overall, the YBMZ technique showed the strongest relation with subjective yield classes. Percentage areal agreement ranged from 24 to 40% for SSMZ and from 32 to 59% for YBMZ. However, the

Table 2 Guidelines for interpreting the Kappa statistic

Kappa statistic (proportion of areal agreement)	Strength of agreement
<0	Poor
0–0.20	Slight
0.21–0.40	Fair
0.41–0.60	Moderate
0.61–0.80	Substantial
0.81–1.0	Almost perfect

From Landis and Koch (1977)

SSMZ technique had larger Kappa statistics compared to the YBMZ technique. Based on these results, SSMZ appears to be more accurate than YBMZ in differentiating areas of low, medium, and high yields.

Based on the three approaches used to compare SSMZ and YBMZ, the former characterizes low, medium, and high productivity areas across agricultural production fields better than YBMZ. However, results from the areal agreement and Kappa statistics suggest that SSMZ falls short of identifying spatial variation completely. Although there are many reasons for this, one is the resolution of the management zones. This is limited by the fertilizer applicator's spray boom width, which is commonly 18 to 27 m wide. Portions of management zones that are smaller than the width of the application boom are assimilated into the surrounding (larger) management zone unit during the smoothing process. This smoothing step is also used by the YBMZ technique; however, this technique is dynamic and so the shape and size of the management zones it delineates are apt to change because of the inclusion of the previous year's yield map.

N-uptake and grain yield across SSMZs

For all site years and all N application rates, mean N uptake generally followed the productivity potential of the SSMZs (Fig. 2). Results from LSD mean separation analysis indicate that the low and high management zones are significantly different, regardless of the N fertilizer rate applied ($p < 0.05$). Likewise, trends observed for grain yield mirrored

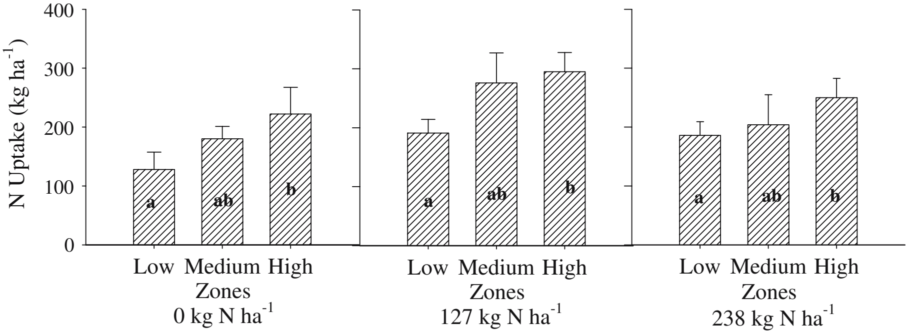

Fig. 2 Mean N uptake for each N application rate across site-specific management zones. Bars with a different letter are significantly different at $p \leq 0.05$, bars with both letters are not significantly different from those with one letter at $p \leq 0.05$. Adapted from Inman et al. (2005)

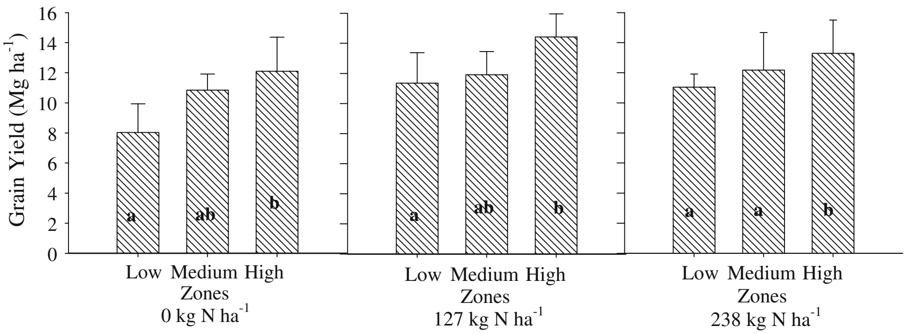

Fig. 3 Mean grain yield for each N application rate across site-specific management zones. Bars with a different letter are significantly different at $p \leq 0.05$, bars with both letters are not significantly different from those with one letter at $p \leq 0.05$. Adapted from Inman et al. (2005)

the productivity potential of the SSMZs. The low and high zones were also found to be statistically different, on the basis of grain yield, for most site-years and N fertilizer rates ($p < 0.05$) (Fig. 3). The medium zone, by contrast, was statistically inseparable from both the low and high zones on the basis of N uptake and grain yield ($p < 0.05$). These results indicate that while SSMZ failed to separate the medium zone from either low or high productivity management zones, it consistently identified areas of low and high productivity zones for N uptake and grain yield across irrigated production maize fields. Regression analysis results (data not presented), for all site-years, indicate that SSMZs are also significantly different with regard to grain yield response to applied N fertilizer ($p < 0.05$). These results suggest that SSMZs have different capacities to utilize applied N fertilizer. Furthermore, considering that the low zone has the lowest N uptake, grain yields and is least responsive to N fertilizer, the results suggest that the low zone, in particular, should be managed differently from the other zones. Based on these results, the SSMZ technique appears to have potential as a tool for differential N fertilizer management across irrigated maize production fields.

Soil properties across SSMZs

Analyses of soil properties are shown in Fig. 4. Across sites-years, commonalities between the results reported above (i.e., N uptake, grain yield and grain yield response to N fertilizer) and soil physical properties are salient. Particularly interesting are the results for bulk density, organic carbon and soil texture. Soil bulk density was significantly different between the low and high zones for all site years, with the low zones having the highest bulk density. Similarly, soil texture was statistically different across site-years between the low and high zones, with the low zones having the largest sand content. In contrast, organic matter was significantly less in the low zones compared to the high ones for all site years. Similar results have been reported by Pilesjö et al. (2005), in which they found significant differences in organic carbon, texture, and other soil properties between management zones delineated using only field topography. The SSMZ delineation technique used here uses bare-soil imagery as one of the three input layers, the tone of which is affected directly by organic carbon. Differences in texture and organic carbon among management zones affect the water availability to the crop as well as the N availability. Since the fields used in this study have soil that is well-drained to excessively well-drained, the availability of

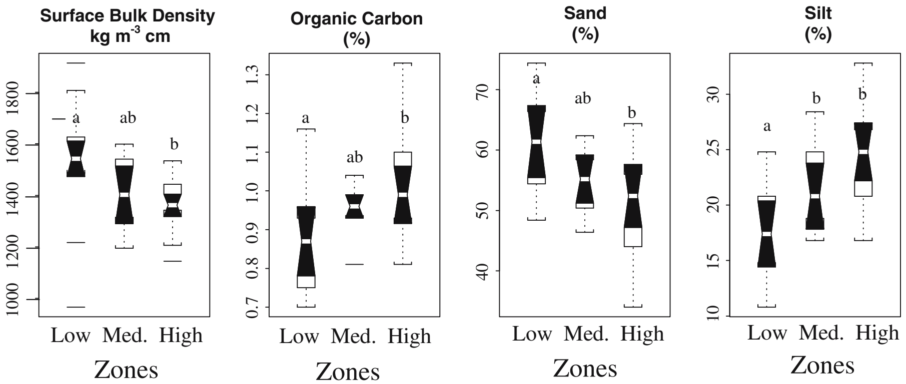

Fig. 4 Box plots of soil properties across site-specific management zones. Within a plot, boxes with different letters are statistically different at $p \leq 0.05$, bars with both letters are not significantly different at $p \leq 0.05$. Adapted from Mzuku et al. (2005)

water is a key factor in nutrient uptake and therefore productivity potential. Based on these results, it can be surmised that, for the sites used in this study, the low zone has soil physical properties that limit crop productivity. As our earlier results have shown, the low zone has soil physical properties that adversely affect crop productivity; thus it logical that the low zone exhibits generally lower N uptake and grain yields as well as a dampened response to N fertilizer (Fig. 4).

Economic analysis of SSMZs

Economic returns were variable across N management strategies. Weighted net returns across management zones for all N management strategies are given in Table 3. Each N management strategy evaluated was profitable at the 2006–2007 maize grain prices of 138 USD per Mg of grain and 0.16 USD per kg N fertilizer. Profitability of the N management strategies depends largely on the prices paid for grain at the elevator as well as the cost of N fertilizer, both of which are apt to fluctuate widely within a given growing season. Net returns ranged from 188 USD to 679 USD ha^{-1}. In two out of three site-years the VYG strategy resulted in the largest net returns (Table 3). The profitability of this strategy can be attributed to optimizing the N fertilizer for each zone. Based on the results presented earlier, the SSMZ technique characterizes areas of differential productivity potential accurately; the differences in the productivity potential of the zones are related to limiting soil properties (e.g., texture, bulk density, and organic matter). Taking into account that these low productivity areas (i.e., low zones) use less N fertilizer and produce lower grain yields, it makes economic sense to apply less N fertilizer to them. Optimum application of N fertilizer to the low management zone, as in the VYG strategy, reduces one of the primary factors that drive net returns. Koch et al. (2004) found that the low production potential zone, managed with the VYG strategy, cost as much as 16% less than other N management strategies and that it was more profitable across a wide range of corn grain and N fertilizer prices than uniform, grid and CYG N management strategies.

Differences in average net returns between the uniform and VYG N management strategies between production level management zones and site-years are shown in Fig. 5.

Table 3 Selected weighted net returns per hectare for each N management strategy from three agricultural fields used in this study

Field	Net returns (USD[a] ha^{-1})			
	N management strategy			
	Uniform	CYG[b]	VYG[c]	Grid[d]
A	409	395	452	188
B	631	579	697	650
C	579	619	610	301

Adapted from Koch et al. (2004)

[a] USD = United States Dollars

[b] CYG = Constant yield goal variable-rate N management strategy

[c] VYG = Variable yield goal variable-rate N management strategy

[d] The Grid strategy used a 0.4-ha soil sampling grid to determine N rate irrespective of management zones

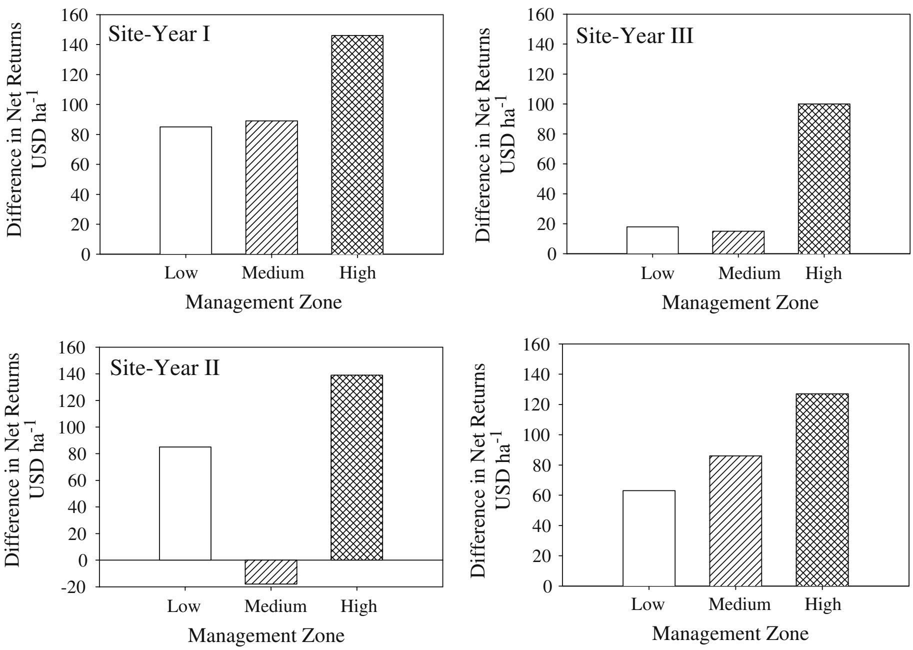

Fig. 5 Average differences in net returns (USD ha^{-1}) between the uniform and VYG N management strategies. Adapted from Inman et al. (2007)

The VYG N management strategy resulted in greater net returns in eight out of nine comparisons. From Fig. 5, it is salient that the greatest difference in net returns between the uniform and VYG strategies is in the high production potential management zones? Averaged across all site years, the VYG strategy resulted in as much as 127 USD ha^{-1} greater net returns than the uniform strategy. Under the VYG N management strategy, more N is applied to the high production potential management zone, where greater yields can be obtained.

Conclusions

This paper provides a synthesis of what has been learned over several years with regard to SSMZs and irrigated maize cropping systems in the Western Great Plains of the USA. Site-specific management zones have been investigated extensively as a tool to assist agricultural producers in making more informed decisions and to optimize N fertilizer management strategies. Through this research, SSMZs have been shown to be a simple and inexpensive way to characterize spatial variation of yield-limiting factors, particularly N, in irrigated maize. Compared to a more data-intensive technique to delineate management zones that included yield monitor data and multi-spectral imagery, the SSMZ technique was found to be more effective. The latter resulted in management zones that characterized differential yield potential across agricultural fields more accurately. Management zones delineated by SSMZ are significantly different with regard to several soil and crop properties. Spatial variation in N uptake, grain yield and grain yield response to applied N, soil bulk density, soil texture and organic carbon content can be characterized adequately using SSMZs. Using the SSMZs as a basis for variable-rate N fertilizer application, N fertilizer use can optimized, thus improving economic returns by as much as 679 USD ha^{-1}. Overall, SSMZs are a practical approach to precise N management in the Western Great Plains region of the USA.

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