Assessment of Field Spatial and Temporal Variabilities to Delineate Site-Specific Management Zones for Variable-Rate Irrigation

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Abstract: Quantification and analysis of field variability are important initial steps in delineating potential variable-rate irrigation (VRI) management zones within an agricultural field. This study seeks to utilize variability in soil physical and chemical properties and in field elevation across a 27-ha field at the Alberta Irrigation Technology Centre (AITC) in southern Alberta, Canada, to define site-specific management zones. All geospatial data were collected during the 2013 and 2014 growing seasons. A stepwise multivariate regression approach was used to investigate how multiple measured parameters affect wheat yield. An unsupervised clustering algorithm, fuzzy c-means, was used to delineate the irrigation management zones. Fuzziness performance index (FPI) and normalized classification entropy (NCE) were used as verification criteria to determine the optimal number of management zones. Results revealed that soil electrical conductivity (EC) and field elevation were better suited for management zone delineation. Three management zones were identified based on the verification criteria using EC and field elevation variables. Measured crop yield differences corresponding to the three noncontiguous management zones were significant. The study area was categorized as low, medium, and high productive zones. The maximum wheat yield (4.80 $\mathrm{t\,ha^{-1}}$) was attained in the high-productivity zone; the lowest (2.22 $\mathrm{t\,ha^{-1}}$), in the low-productivity zone. **DOI: 10.1061/(ASCE)IR.1943-4774.0001222.**

Author keywords: Soil heterogeneity; Management zones; Center-pivot irrigation system; Data clustering; Field mapping; Southern Alberta.

Introduction

Alberta accounts for over 75% of the irrigated area in Canada (Alberta Water Council 2007), and the irrigation industry is the major consumer of fresh water in southern Alberta. Approximately 70% of the irrigated land in southern Alberta is irrigated with a center-pivot irrigation system (CPIS) (Alberta Agriculture and Forestry 2014). Alberta's irrigation sector, under its Water for Life Strategy, is committed to improving water and energy use efficiency and crop productivity by 15% through conversion or modification of existing irrigation systems to low-pressure CPIS (Alberta Water Council 2007; AECOM 2009; Alberta Irrigation Projects Association 2010). Adoption of variable-rate irrigation (VRI) in southern Alberta is expected to improve water application, taking into account field variability, increased water use efficiency, crop productivity, and profitability.

Li et al. (2008) noted that the current trend is to implement a site-specific management strategy, rather than a whole-field approach, to overcome field variability. For VRI, defining site-specific management zones (SSMZs) is challenging because of a complex combination of spatial and temporal variability that affects crop yield (Fridgen et al. 2004). Topographic attributes and apparent soil electrical conductivity (EC_a) are indicators of plant-available water and are effective parameters in management zone delineation (Fridgen et al. 2000). For example, elevation differences across a field can cause water ponding with movement of water from high-elevation areas toward low-elevation areas (Sadler et al. 2000). Kachanoski et al. (1988) reported a strong relationship between soil water content and EC_a. The nature of this relationship varies by location and time.

Topographic attributes and EC_a are the most widely used variables for SSMZ delineation (Fridgen et al. 2000). Fridgen et al. (2004) used EC_a, elevation, and field slope to identify SSMZs using an unsupervised clustering algorithm. *Management Zone Analyst* (*MZA*) software with a fuzzy c-means clustering algorithm (Fridgen et al. 2004) was used to cluster data into different groups. The optimal number of clusters was selected using verification criteria: the fuzziness performance index (FPI) and the normalized classification entropy (NCE) index. The FPI represents least membership sharing, and NCE represents the amount of disorganization of a fuzzy C-partition. Boluwade et al. (2016) investigated a fuzzy c-means algorithm and regionalization with a constrained clustering and partitioning (REDCAP) technique for delineating SSMZs

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using EC_a and elevation maps. The study found that the fuzzy c-means algorithm using *MZA* software generated a cost-effective solution for delineating SSMZs. Pelcat et al. (2004) employed the fuzzy c-means clustering algorithm using satellite imagery, and this offered the best potential SSMZs in terms of cost. A web-based decision support tool, Zone MAP, was developed at North Dakota State University, in Fargo, North Dakota, (Zhang et al. 2010) to determine the optimal number of zones using remotely sensed images and field data. The SSMZs developed using Zone MAP were consistent with management zones delineated using traditional means.

Spatial and temporal field variability results in uneven distribution of soil water content (Xiang et al. 2007). Uneven field elevation can result in dry zones in high-elevation areas and ponding in low-elevation areas. The SSMZs can be created taking soil and topographic variations into account in order to define areas of a field with similar water requirements (Xiang et al. 2007). Redulla (2002) assessed the effects of spatial variability of pH, nutrient availability, and soil texture on four potato fields. They identified that soil texture had the strongest correlation with yield. Crop yield data and related indices such as the normalized difference vegetation index (NDVI) can be used in combination with soil chemical and physical characteristics to define SSMZs (Li et al. 2008). Farmer-defined management zones were investigated for variable-rate application (VRA) based on past management experiences, topography, soil color, and aerial images in Colorado (Fleming et al. 2000). The results indicated that farmer-developed management zones can also be considered an effective strategy in conjunction with ground assessment (Fleming et al. 2000). Fleming et al. (2004) developed management zones for VRA based on soil color and farmer experience, and compared these with management zones developed using EC_a. Their work indicated that both methods were effective in terms of identifying homogeneous subregions but that EC_a was more effective in delineating distinct management zones. Hornung et al. (2006) found that including more data layers in the SSMZ delineation process did not necessarily guarantee the accuracy of the technique. These studies verified that the method with fewer information layers was as precise as the method with more data layers. Optimal choice of the most effective variables in management zone delineation models minimizes the costs associated with data collection and maximizes the effectiveness of prescription maps.

The overall goal of this study was to develop SSMZs within a field irrigated with a CPIS and retrofitted with a commercial VRI package. Specific objectives were (1) to investigate a stepwise multivariate regression approach to identify the optimum number of variables for management zone delineation, (2) to delineate potential management zones using a fuzzy c-means clustering algorithm based on the most influential and effective parameters, and (3) to verify the delineated management zones with measured crop yield.

Materials and Methods

Study Area and Irrigation System

The experimental site was a 27-ha circular field irrigated with a five-span CPIS at the Alberta Irrigation Technology Centre (AITC). The AITC is located in southern Alberta at latitude 49.69°N and longitude 112.74°W with a mean elevation of 905 m above mean sea level. The experimental field was situated in the St. Mary River Irrigation District (SMRID), east of the city of Lethbridge (Fig. 1). The SMRID irrigation district comprises a 137,000-ha irrigated area, and its irrigation water is taken from the St. Mary River (Alberta Agriculture and Forestry 2014). Average maximum and minimum growing season temperatures in Lethbridge were 21°C and 6°C, respectively, over the period from 2000 to 2015 (Alberta Agriculture and Forestry 2015a). The mean annual precipitation was 384 mm and varied from 207 to 747 mm over the period from 1971 to 2015 (Alberta Agriculture and Forestry 2015b).

A five-span CPIS with a lateral length of 294 m retrofitted with a commercial VRI (Valmont Industries, Valley, Nebraska) was used to irrigate the experimental site. The system was equipped with

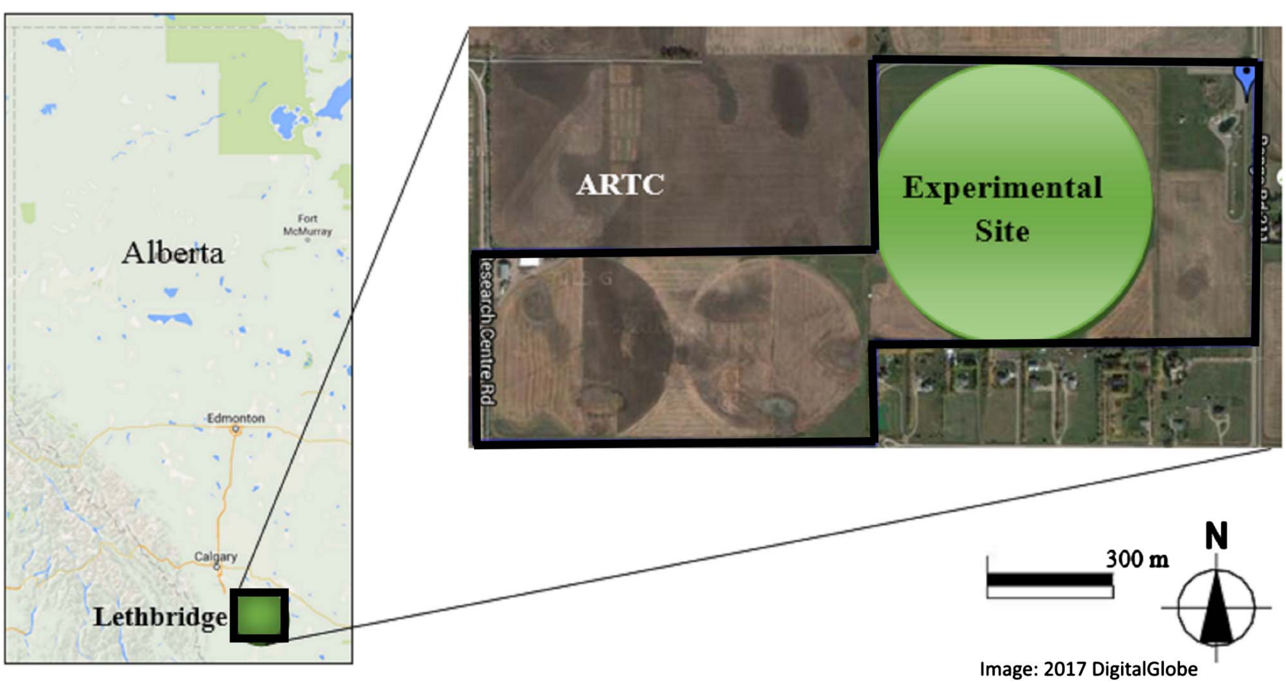

Fig. 1. Study site in southern Alberta (© Google, image © 2017 DigitalGlobe)

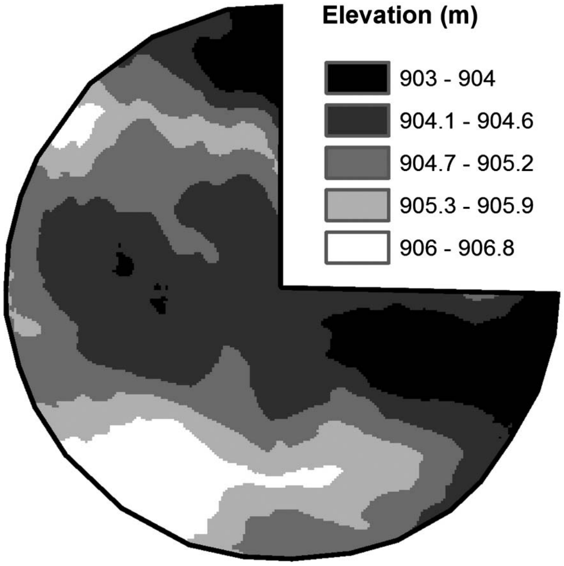

Fig. 2. Field elevation map

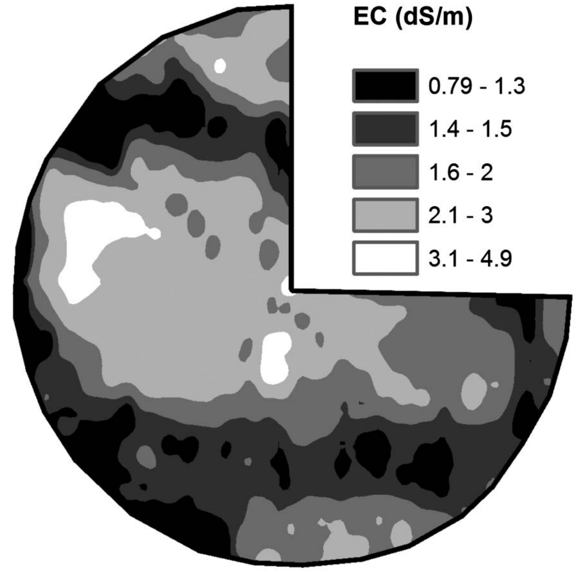

Fig. 3. Soil EC map

Nelson rotator sprinkler nozzles (R3000, D6-Red) and 1.2–bar pressure regulators (Nelson Irrigation, Walla Walla, Washington). The sprinkler package [low-elevation spray application (LESA)] comprised 129 sprinklers divided into 12 sprinkler banks. Each sprinkler bank had 10–12 sprinklers.

Field Elevation

Fig. 2 shows the field elevation map obtained using a real-time kinematic (RTK) global navigation satellite system (GNSS) receiver. The area exhibits an elevation ranging from 907 m at the highest point in the southwest portion of the field and 903 m at the lowest point in the east and north portions of the field. In terms of water movement, the highly variable elevation in this field is a critical factor in determining management zones. Because of the lack of a drainage system, excess water in low-elevation areas affects plant growth and quality during heavy rainfall in approximately 20% of the total area. Conversely, in high-elevation areas, water loss due to surface runoff reduces the deep penetration of water to the effective plant root zone and consequently limits plant growth because of water deficits.

Soil Electrical Conductivity

In 2013 EC_a was measured using an EM38 instrument (Geonics Limited, Mississauga, Ontario, Canada) and the Veris 3100 soil-mapping machine (Veris Technologies, Salina, Kansas). The data layer collected by the EM38 instrument is included in this paper. Soil samples were collected for soil electrical conductivity (EC) measurement at various points within the EM38 survey area. There was a strong positive relationship between the EC_a and EC for the study area. This relationship was used to make predictions of EC ($dS\,m^{-1}$) from EC_a ($mS\,m^{-1}$) data. High-density geospatial EC maps were produced based on ordinary kriging interpolation using the commercial GIS package *ArcGIS*. The top-right 90° radial sector was not mapped because of ongoing farming operations. Maps of elevation (Fig. 2) and EC (Fig. 3) indicate a strong inverse relationship between EC and elevation (low-elevation areas have greater EC; high-elevation areas, lower EC) in the top-left and bottom-left 90° radial sectors. However, in the most eastern part of the study site, this inverse relationship is not strong. The lateral movement of water and nutrients from high elevations to low elevations due to steep land slopes may be the reason for a strong inverse relationship between EC and elevation in the western part of the site. Highly variable elevation created areas of ponded water, and the lack of adequate drainage caused higher salinity in the spots mostly situated in the western part of the study site. However, this was not the case in the easternmost part of the field because of the flatter elevation.

Data Collection from Experimental Plots

In the 2013 growing season, two experimental blocks (Fig. 4) were selected for data collection. Block 1 (B1) was situated in high-EC, low-elevation areas; Block 2 (B2), in medium-EC, medium-elevation areas. In 2014 Block 3, (B3) was added in the low-EC, high-elevation areas. Each block was divided into nine experimental

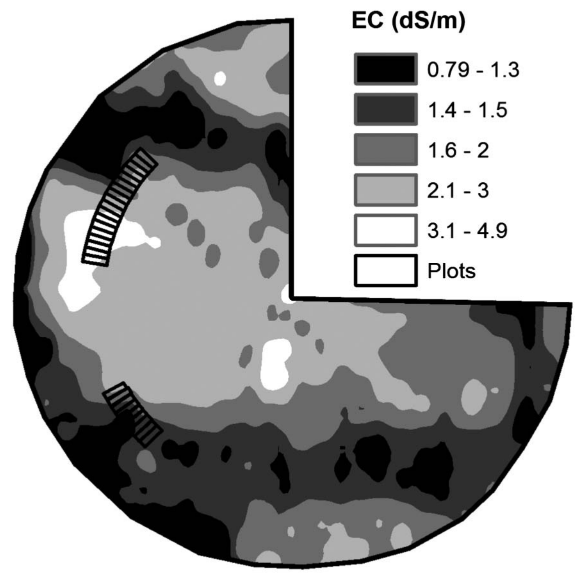

Fig. 4. Overlay of experimental blocks on EC map (B1, B2, and B3 = high-, medium-, and low-EC areas, respectively)

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plots for data collection purposes, and each experimental plot had an area of 192 m^2. The mean EC in the 0–90-cm depth ranged 1.8–7.75 $dS\,m^{-1}$, 0.5–4.1 $dS\,m^{-1}$, and 0.37–2.6 $dS\,m^{-1}$ for B1, B2, and B3, respectively. The elevation ranged 904–904.6 m, 904.6–905.2 m, and 905–906.1 m for B1, B2, and B3, respectively.

Crop Data

In 2013 and 2014, Hard Red Spring (HRS) wheat was sown with a seeding rate of 158 $kg\,ha^{-1}$ in the experimental blocks. In 2013 HRS wheat (Carberry variety) was planted on May 2 and harvested on September 4. In 2014 the same HRS wheat variety was planted on May 15 and harvested on September 18. All experimental blocks were fertilized equally, and fertilizer was applied according to Alberta Agriculture and Forestry recommendation. A total of 218 and 195 $kg\,ha^{-1}$ of nitrogen (46-0-0) was applied in the 2013 and 2014 growing seasons, respectively. A plot-sized combine (Wintersteiger Ag, Ried im Innkreis, Austria) was used to harvest the crop in the experimental plots. Three sampling areas were selected to collect the crop yield in each plot.

Soil Physicochemical Properties

Georeferenced soil samples were taken from three depths in three locations (0–30 cm, 30–60 cm, and 60–90 cm) in each experimental plot in 2013 and 2014. A total of 243 soil samples were taken from 81 locations at three depths and prepared for chemical and physical analyses.

Particle size analysis (sand, silt, and clay) was performed using a hydrometer with the Bouyoucos method (Sheldrick and Wang 1993). A saturated soil paste was created (1:2 suspension) and its soil pH was determined directly. Electrical conductivity of the saturated paste and solution concentrations of calcium (Ca^{2+}), magnesium (Mg^{2+}), potassium (K^+), and sodium (Na^+) were measured (Janzen 1993). The amount of Ca^{2+} and Mg^{2+} in the paste extract was determined by flame atomic absorption spectrometry; the amount of Na^+ and K^+, by flame photometer (Baker and Suhr 1982). Undisturbed soil samples at the same three sampling depths were taken, and soil bulk density was determined. Organic matter in the soil was measured by the loss-on-ignition procedure (Goldin 1987).

Irrigation Applications

Ideal conditions for growing HRS wheat in southern Alberta require 420–480 mm of water per growing season (Alberta Agriculture and Forestry 2013). Irrigation frequency and depth were recommended by Alberta Agriculture and Forestry using the Alberta Irrigation Management Model (*AIMM*). A total of four irrigations were applied in the 2013 growing season on July 16 and August 19, 21, and 27. In 2014 there were six irrigation events on July 9, 11, 28, and 29 and August 6 and 8. In a few cases, the required irrigation amount was applied in two consecutive irrigation events to prevent surface runoff and to allow for the infiltration of water. The total applied irrigation depths were 81.27 and 104.2 mm in 2013 and 2014, respectively. Mean application uniformity during the irrigation events over the two years was 92%, and wind speed ranged between 1.2 and 6.6 $m\,s^{-1}$.

Soil Water Tension

Soil water tension was measured continuously at five-min intervals using Hortau soil tension sensors [Irrolis MultiSense Tx3 (#2000) Web Based, Hortau, Quebec City, Quebec, Canada] in the experimental plots. In 2013 and 2014, respectively, the 18 and 27 soil tension sensors were installed to a depth of 30 cm, and Hortau

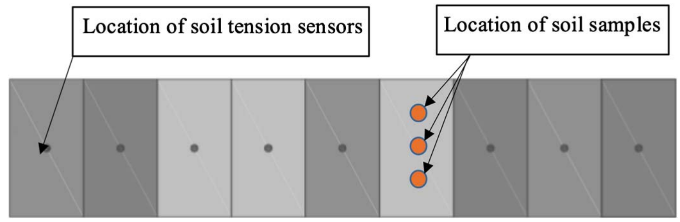

Fig. 5. Soil tension sensor location in experimental plots

TX[3] field monitoring stations were used to send data to a base station (Fig. 5).

Statistical Analysis

A stepwise multivariate regression model was used [IBM (*SPSS*)] with forward selection to determine the optimum number of variables. ANOVA was performed (*SAS 9.4*) to compare the wheat yield differences at the 95% level of probability in three experimental blocks. A Shapiro-Wilk normality test was used to determine whether or not the data were drawn from a normally distributed population.

Management Zone Delineation

The fuzzy c-means clustering technique classifies observation data into C groups of distinct clusters. Three matrices are involved in the clustering procedure, and the technique has been described mathematically numerous times in the literature (Bezdek 1981; Odeh et al. 1992; Fridgen et al. 2004; Li et al. 2008; Boluwade et al. 2016).

Cluster Validity Functions

To evaluate the performance of the fuzzy c-means algorithm and the delineated management zones, the FPI and NCE were adopted (Bezdek 1981; Odeh et al. 1992; Boydell and McBratney 2002). The FPI is a measure of the degree of separation and ranges from 0 to 1; the NCE indicates the amount of disorganization of a fuzzy C-partition and ranges from 0 to 1 also. As the FPI approaches 0, membership sharing decreases and clusters become more distinct. Conversely, when it approaches 1, membership sharing increases and clusters are less distinct (Fridgen et al. 2000, 2004; Pelcat et al. 2004). For the NCE, values near 0 indicate greater organization within cluster members whereas values approaching 1 indicate greater disorganization.

In developing the SSMZs, *MZA* software was used to calculate descriptive statistics, perform the unsupervised c-means fuzzy algorithm, and provide two verification indices (Fridgen et al. 2004) to determine the optimum number of management zones. The *MZA* was performed by setting the clustering parameters based on the recommended values by Odeh et al. (1992) and Fridgen et al. (2004). The Mahalanobis measure of similarity (Odeh et al. 1992; Fridgen et al. 2004) was selected for the clustering procedure (minimum number of zones = 2, maximum number of zones = 12, fuzziness exponent = 1.3, maximum number of iterations = 300, and convergence criterion = 0.0001), and values were determined for the clustering process.

Results and Discussion

Stepwise Multivariate Regression Approach

Descriptive statistics, including means, minimum and maximum values, and standard deviation (SD), for soil physical and chemical

Table 1. Descriptive Statistics of Study Site Measured Parameters

Variable	Mean	Minimum	Maximum	SD
pH	7.77	7.53	7.97	0.10
EC ($dS\,m^{-1}$)	2.6	0.37	7.75	2.34
I (mm) 2013	90.34	80.60	106.40	7.36
I (mm) 2014	102.01	50.41	143.75	24.04
ST (kPa) 2013	8.34	0.29	16.11	5.56
ST (kPa) 2014	10.83	3.50	21.98	5.20
OM (%)	2.59	2.10	3.10	0.21
Sand (%)	51.78	42.00	58.33	4.86
Clay (%)	24.23	21.00	30.67	2.57
Silt (%)	23.99	18.00	30.33	2.90
BD ($g\,cm^{-3}$)	1.63	1.40	1.90	0.18
Elevation (m)	905.00	903.00	907.00	0.34

Note: BD = bulk density; I = irrigation; OM = organic matter; SD = standard deviation; ST = soil tension.

properties, elevation, total irrigation during the growing seasons, and average soil water tension during the growing seasons are summarized in Table 1.

According to particle size analysis, soil textures in the depth 0–90 cm were mostly sandy clay loam (SCL). The average particle size distribution was 52% sand, 24% clay, and 24% silt. The mean organic matter content in the topsoil (0–30 cm) was 2.6%. The EC varied widely across the experimental plots and ranged between 0.37 and 7.75 $dS\,m^{-1}$. However, as a result of interpolation, the predicted EC map (Fig. 3) from EM38 measurements showed that the EC ranged between 0.79 and 4.9 $dS\,m^{-1}$, thus masking the underlying high EC variability in B1.

Stepwise multivariate regression was carried out with 10 independent variables, and forward selection was conducted separately for the 2013 and 2014 growing seasons. Dependent variables such as Ca^{2+}, Mg^{2+}, K^{+}, and Na^{+} were removed from the input variables because of strong correlation with EC. Pearson's correlations between each variable and the crop yield value are listed in Table 2. It was found that elevation and EC strongly correlated with the crop yield in both years. There was a significant inverse relation between EC and crop yield with R^2 values of −0.46 and −0.61 in 2013 and 2014, respectively. A positive correlation was found between field elevation and crop yield with R^2 values of −0.47 and −0.52 over the two years. Elevation and EC had the most influence on yield, with higher yields observed at higher elevation and lower EC areas. Table 3 lists the models resulting from the stepwise approach for the 2013 and 2014 growing seasons. A better model was generated between pH and field elevation with crop yield in 2013. In 2014 a better relationship was established between EC and crop yield. These results are in agreement with those obtained by Peralta et al. (2013).

Field measurement of all soil physicochemical and field information was not feasible because of limitations of time and cost. For this reason, the easier measurements and inexpensive field information such as EC and elevation are usually preferred to delineate SSMZs for an irrigated field. There are a handful of parameters for management zone delineation; however, the delineated management zone should be accurate, simple, and inexpensive to collect the minimum data requirement. Stepwise analysis of the available variables indicated that EC, pH, and field elevation are the most important parameters to include when performing management zone delineation for VRI in the study area. Furthermore, because the relatively higher R^2 values (Table 2) suggest a strong link between EC and field elevation with crop yield, these variables can be of major value in delineating site-specific management zones. Moreover, EC and field elevation data sets are becoming easily accessible, making management zone delineation cost-effective.

Management Zone Delineation

Management zone delineation for VRI using an unsupervised clustering algorithm, fuzzy c-means, has been extensively studied in recent years. The fuzzy c-means algorithm provides a couple of

Table 2. Pearson's Correlation Matrix for All Variables

Variable	PH	EC	I, 2013	I, 2014	ST, 2013	ST, 2014	OM	Sand	Clay	Silt	BD	Elevation
PH	1.00	—	—	—	—	—	—	—	—	—	—	—
EC	−0.01	1.00	—	—	—	—	—	—	—	—	—	—
I, 2013	0.05	0.04	1.00	—	—	—	—	—	—	—	—	—
I, 2014	0.07	0.03	0.69	1.00	—	—	—	—	—	—	—	—
ST, 2013	−0.48	−0.49	−0.16	−0.45	1.00	—	—	—	—	—	—	—
ST, 2014	−0.23	−0.07	−0.56	−0.65	0.71	1.00	—	—	—	—	—	—
OM	−0.42	−0.25	−0.20	−0.20	0.62	0.33	1.00	—	—	—	—	—
Sand	0.54	−0.18	0.14	0.16	−0.39	−0.35	−0.47	1.00	—	—	—	—
Clay	−0.41	0.21	−0.20	−0.24	0.34	0.49	0.42	−0.83	1.00	—	—	—
Silt	−0.53	0.14	−0.09	−0.09	0.35	0.22	0.43	−0.95	0.60	1.00	—	—
BD	−0.03	0.45	0.20	0.25	−0.31	−0.28	−0.12	−0.01	−0.09	0.07	1.00	—
Elevation	−0.14	−0.67	0.08	0.13	0.68	0.17	0.24	0.05	0.04	−0.10	−0.19	1.00
Yield, 2013	0.28	−0.46	0.18	0.05	0.15	−0.18	0.29	0.02	−0.05	0.00	−0.11	0.47
Yield, 2014	−0.17	−0.61	−0.04	0.08	0.16	−0.11	0.32	−0.06	−0.03	0.10	−0.18	0.52

Note: BD = bulk density; I = irrigation; OM = organic matter; ST = soil tension.

Table 3. Stepwise Models for 2013 and 2014 Growing Seasons

Year	Selected variables	Model	R^2	P value
2013	Elevation	Yield = 0.62 (elevation) −558.25	0.22	0.005[a]
	Elevation and pH	Yield = 0.69 (elevation) + 1.02 pH − 628.71	0.34	0.002[a]
2014	EC	Yield = 4.62−0.174 EC	0.38	0.000[a]

[a]Significant ($p < 0.05$).

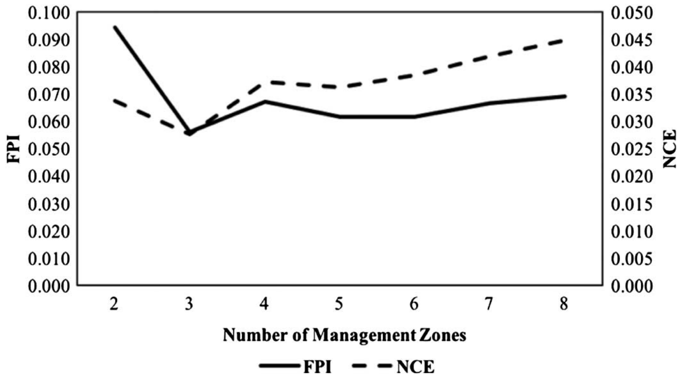

Fig. 6. FPI and NCE for study site

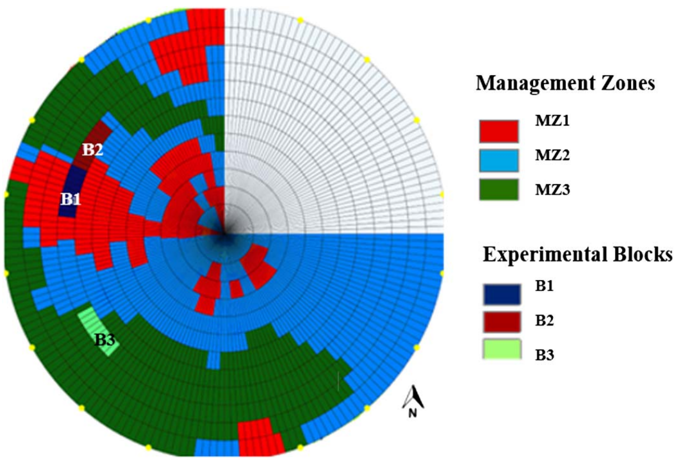

Fig. 7. Three potential management zones for study site produced by *VRI Prescription 6.5*

verification criteria to find the optimum number of management zones. It was used to delineate irrigation management zones using EC and field elevation parameters for the study site. The FPI and NCE were used to identify the optimum number of management zones. The minimum FPI and NCE were observed (Fig. 6) for three clusters, indicating an optimum number of three management zones.

A management zone map was produced (Fig. 7). The classification of the study site into zones followed the EC and elevation patterns of the field. Management Zone 1 (MZ1) included the high-EC area with an average EC of 5.35 $dS\,m^{-1}$ and an elevation of 903.5 m. Management Zone 2 (MZ2) included the medium-EC area with an average EC of 1.39 $dS\,m^{-1}$ and an elevation of 904.9 m. Management Zone 3 (MZ3) included the low-EC area with an average EC of 0.74 $dS\,m^{-1}$ located in the high-elevation area with a mean elevation of 904.9 m.

Crop Yield Analyses for Management Zone Validation

Further analyses were carried out to validate the appropriateness of the management zones using measured crop yield in the 2014 growing season from the experimental blocks located in the delineated management zones (the 2013 data are not shown because they represent only two management zones). The statistical analyses identified that the crop yields were significantly different among the three zones ($p < 0.05$). The crop yield measurement and zone delineation led to the study site being categorized as three different productive areas: low, medium, and high—MZ1, MZ2, and MZ3, respectively. The highest crop yield (4.80 $t\,ha^{-1}$) was produced in MZ3, where EC was low and elevation was high. The lowest crop yield was in MZ1, situated in the high-EC, low-elevation area (Table 4). The lower yield in MZ1 can be related to soil salinity and water ponding. The salt tolerance threshold and slop for the wheat yield were 5.9 $dS\,m^{-1}$ and 3.8% (Wallender and Tanji 2011), respectively. The wheat was rated as tolerant to salinity, but salinity higher than 5.9 $dS\,m^{-1}$ can negatively impact yield. Average EC was 5.35, 1.55, and 0.74 $dS\,m^{-1}$ for MZ1, MZ2, and MZ3, respectively, and the crop yield was mostly lower in MZ1 because of a combination of water ponding and salt accumulation over the growing season.

It can be seen from Table 4 that soil physical properties were not the main driver of field variability but that soil EC was significantly different in the management zones. Salt accumulation due to seepage in low-elevation areas resulted in low crop yields at several locations. Water moves laterally from high elevations to low elevations because of overirrigation or heavy rainfall and eventually creates waterlogged areas in low-elevation areas during wet years. Lack of a drainage system at this study site exacerbated the impact of salinity on crop growth in low-elevation areas.

Conclusions

The suitability of a stepwise multivariate regression in conjunction with fuzzy c-means clustering to create the optimum number of management zones based on limited variables was assessed. It was found that such an approach can be used to determine the most appropriate variables for management zone delineation. Here the most appropriate variables were determined to be soil EC, pH, and field elevation. Because soil EC and elevation can be obtained with on-the-go soil-sensing technology at a relatively low cost, it was found that delineating irrigation management zones for VRI based on EC and field elevation is more effective.

A fuzzy c-means unsupervised clustering technique was successfully used to develop management zones based on the soil EC and field elevation. The FPI and NCE validity criteria identified that three zones were optimal for the study area. Statistical analysis showed that the delineated management zones were significantly different in terms of crop yield. The study site was categorized into low- (MZ1), medium- (MZ2), and high-productivity (MZ3) areas that can be managed individually in terms of agricultural input application. The highest wheat yield (4.80 $t\,ha^{-1}$) was obtained

Table 4. Mean Soil Physicochemical Properties at Soil Depth 0–90 cm and Crop Yield in Experimental Plots in the Three Management Zones (2014)

Zone	Sand (%)	Clay (%)	Silt (%)	pH	OM (%)	EC ($dS\,m^{-1}$)	BD $g\,m^{-3}$	Y 2014 ($t\,ha^{-1}$)	Level	*P* values
MZ1	50.2	25.4	24.4	7.74	2.57	5.35	1.79	2.22	MZ1 vs. MZ2	0.0001[a]
MZ2	52.9	23.3	23.8	7.80	2.61	1.39	1.55	4.28	MZ1 vs. MZ3	0.0001[a]
MZ3	53.3	23.4	23.3	7.76	2.59	0.74	1.58	4.80	MZ2 vs. MZ3	0.004[a]

Note: BD = bulk density; EC = electrical conductivity; OM = organic matter; Y 2014 = crop yield in 2014.
[a]Significant ($p < 0.05$).

in areas where EC was low (0.74 $dS\,m^{-1}$) and elevation was high (906 m). The lowest yield (2.22 $t\,ha^{-1}$) was obtained in the low-productivity zone, situated in the high-EC (5.35 $dS\,m^{-1}$), low-elevation (903.5 m) areas.

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