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Delineating site-specific management zones for pH-induced iron chlorosis

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Abstract Iron chlorosis can limit crop yield, especially on calcareous soil. Typical management for iron chlorosis includes the use of iron fertilizers or chlorosis tolerant cultivars. Calcareous and non-calcareous soil can be interspersed within fields. If chlorosis-prone areas within fields can be predicted accurately, site-specific use of iron fertilizers and chlorosis-tolerant cultivars might be more profitable than uniform management. In this study, the use of vegetation indices (VI) derived from aerial imagery, on-the-go measurement of soil pH and apparent soil electrical conductivity (EC_a) were evaluated for their potential to delineate chlorosis management zones. The study was conducted at six sites in 2004 and 2005. There was a significant statistical relationship between grain yield and selected properties at two sites (sites 1 (2005) and 3), moderate relationships at sites 2 and 4, and weak relationships at site 5. For sites 1 (2005) and 3, and generally across all sites, yield was predicted best with the combination of NDVI and deep EC_a. These two properties were used to delineate chlorosis management zones for all sites. Sites 1 and 3 showed a good relationship between delineated zones and the selected properties, and would be good candidates for site-specific chlorosis management. For site 5, differences in the properties between mapped zones were small, and the zones had weak relationships to yield. This site would be a poor candidate for site-specific chlorosis management. Based on this study, the

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delineation of chlorosis management zones from aerial imagery combined with soil EC_a appears to be a useful tool for the site-specific management of iron chlorosis.

Keywords Iron chlorosis · Soil pH · Management zone delineation

Introduction

Much of the soil used for crop production in the Great Plains is derived from calcareous parent material, resulting in carbonate accumulations that can lead to iron chlorosis in crops. Excess carbonates in calcareous soil can raise soil pH and inhibit plant availability of micronutrients such as iron and manganese (Kaspar et al. 2004; Thomas 1996). Certain crops, such as soybean, maize and grain sorghum are particularly susceptible to iron chlorosis under such conditions. Soil composition, environmental factors, and plant iron deficiency response mechanisms influence the incidence of iron chlorosis. However, the key underlying cause of iron deficiency on calcareous soil is limited iron uptake and subsequent translocation and utilization within plants because of the high bicarbonate ion concentration in the soil (Godsey et al. 2003; Mengel 1994). The primary effects of bicarbonate are the neutralization of the H^+ ion in the rhizosphere, the reduction of plasma membrane activity of roots and an increase in root internal pH (Loeppert et al. 1994). As soil solution pH and concentration of bicarbonate increase, the solubility of iron decreases even though total iron in the soil might be substantial. In many cases, chlorotic leaves may have higher Fe concentrations than non-chlorotic leaves. This suggests that Fe uptake by roots and translocation in the plant is not a primary issue, but rather the blocking of Fe^{3+} reduction in plant tissue (Mengel 1994; Wallace et al. 1976).

Iron chlorosis symptoms in the Great Plains are often associated with high calcium carbonate levels or soil that is poorly drained due to clay accumulation, with elevated soluble salts and perhaps high sodium saturation (Loeppert and Hallmark 1985; Franzen and Richardson 2000; Penas and Wiese 1990). Often calcareous and noncalcareous soil is interspersed on a landscape, making uniform iron fertilizer application uneconomic. Foliar application of iron fertilizers can correct iron deficiencies, but multiple applications are often necessary which limit the economic feasibility of this approach. The most effective stable iron chelate, FeEDDHA (ferric ethylenediamine di(o-hydroxyphenylacetate) currently costs about \$69 ha^{-1} for a single soil or foliar treatment to provide 4.5 kg Fe ha^{-1}. Godsey et al. (2003) observed that $FeSO_4 \cdot 7H_2O$ seed row application increased maize yield on soil with a high pH. Goos and Johnson (2000) found that selecting tolerant cultivars provided a greater increase in yield than either FeEDDHA foliar spray or seed treatment of soybean planted in narrow-rows on calcareous soil. Lingenfelser et al. (2005) compared the use of different rates of iron sulfate fertilizers placed with the seed, iron foliar spray, iron chelate seed treatment, plant residue levels and a resistant genotype, and concluded that the use of a resistant genotype appeared to be the most effective treatment to reduce iron deficiency of soybean in Kansas. Many studies concur that the use of chlorosis-tolerant varieties of both maize and soybean is the most practical approach of avoiding iron deficiency on calcareous soil (Hansen et al. 2003; Imas 2000).

When calcareous and non-calcareous soils are interspersed in a landscape, uniform treatments with soil or foliar application of iron fertilizers or the planting of chlorosis-resistant cultivars might not be the most profitable approach. It will depend on the relative ratio of chlorosis-prone areas in the field to the rest of the field. With the advent of site-specific crop management technologies, targeted chlorosis management is now possible and might result in increased profitability, provided that chlorosis-prone areas within a field are relatively stable and predictable. Technology now exists for on-the-go measurement of soil pH and apparent electrical conductivity (EC_a) at a high spatial density (Adamchuk et al. 2007), which might be useful for delineating the areas of fields most prone to iron chlorosis. Soil EC_a is also a potential tool for assessing soil properties related to iron chlorosis, such as salinity, texture, and moisture (Hartsock et al. 2000; Williams and Hoey 1987). On-the-go measurement of soil pH can provide accurate maps of areas within fields with elevated pH, and in particular areas that might have free carbonates in the root zone.

Chlorosis can be identified by leaf color, therefore remote sensing of the growing crop may be used to detect its presence in a crop. Remote sensing methods for growing crops are based on reflectance measurements that indicate the photosynthetic activity of vegetation. Vegetation indices (VI) calculated from high resolution natural color and near-infrared (NIR) aerial photographs might be useful for detecting chlorosis and delineating chlorosis-prone areas within a field. The normalized difference vegetation index (NDVI) (Rouse et al. 1974) is the most widely used index to examine the accumulation of green biomass as well as photosynthetically active radiation, and it has been related to certain vegetation signatures and conditions (Adams et al. 2000; Bastiaanssen et al. 2000; Tucker 1979). The green normalized difference vegetation index (GNDVI), described by Gitelson and Merzylak (1996), substitutes reflectance in green wavelengths for red in the NDVI equation. Research with crops that have a large biomass such as maize has shown that GNDVI is more strongly associated with variability in leaf chlorophyll, nitrogen content and grain yield than NDVI (Shanahan et al. 2001).

Since leaf iron concentration is strongly correlated with leaf chlorophyll content and leaf reflectance (Mariotti et al. 1996), aerial imagery, vegetation indices, soil information and the farmer's experience might be of value in delineating chlorosis management zones. In zones prone to iron chlorosis the use of seed-applied iron fertilizer, chlorosis-tolerant cultivars, or foliar application of iron fertilizer might be profitable, whereas their use over the entire field might not be so.

The objectives of this study are to investigate the potential use of information at a high spatial density (aerial imagery, on-the-go pH and EC_a) to delineate iron chlorosis management zones for crops such as soybean and maize that are sensitive to iron chlorosis stress. These spatial data layers were chosen as they are also related to crop yield potential (Dobermann and Ping 2004; Fraisse et al. 2001; Johnson et al. 2003).

Materials and methods

Site description

The study was conducted in 2004 and 2005 on five fields in central and western Nebraska (Fig. 1). All sites were irrigated; sites 1, 2 and 5 were furrow-irrigated, and sites 3 and 4 were irrigated with center-pivot sprinkler systems. Site 1 was used in both 2004 and 2005. Table 1 gives the field size and soil taxonomic descriptions of soil series present at each site. At all sites, cooperating farmers planted part or all of the field to a maize hybrid considered to have good yield potential, but is susceptible to iron chlorosis—P34N42 (Pioneer Hi-Bred International, Johnston, IA, USA). In addition, site 1 was also planted to soybean in 2005—a crop that is more sensitive to iron chlorosis than maize.

Fig. 1 Study locations within Nebraska, USA

Soil measurements

Soil surface pH and EC_a were measured in April 2004 and April 2005 using a Veris Mobile Sensor Platform equipped with Veris® EC Surveyor™ 3150, and the Soil pH Manager™ (Veris Technologies, Salina, Kansas, USA[1]). Measurements were made at a density of approximately 7–12 samples ha^{-1} for pH and 106–190 measurements ha^{-1} for EC_a. Soil pH samples were taken at 10–12 s intervals on an approximate swath-width of 15–20 m, resulting in samples being typically 20–25 m apart. Soil EC_a was measured to a depth of approximately 30 cm for shallow EC_a (EC_as), and about 90 cm for deep EC_a (EC_ad). Soil samples for pH were taken at a fixed depth of 5–10 cm. The data were georeferenced with a DGPS (Differential Geographic Positioning System) receiver (GPS 16 HVS, Garmin International, Inc., Olathe, Kansas, USA) with WAAS (Wide Area Augmentation System) differential correction and stored in a data logger.

Aerial imagery

Natural color and near-infrared aerial photographs, which were georeferenced and ortho-rectified to remove topographic distortion, were provided by Cornerstone Mapping Inc., Lincoln, Nebraska, USA. Photographs with a resolution of 0.3 m $\times$ 0.3 m were taken during crop vegetative growth stages on 18 July 2004 and 28 July 2005.

Yield mapping

For all sites, maps of grain yield were provided by the producers. Prior to harvesting the study area each yield monitor was calibrated according to the manufacturer's specifications and producer's experience. Raw yield data were processed with SMS Advanced 5.52 software (Ag Leader Technology, Inc, Ames, IA, USA), and yield measurement errors were removed by Yield Editor 1.01 software (USDA-ARS, Cropping Systems and Water Quality Unit, University of Missouri-Columbia, Columbia, Missouri, USA) (Sudduth and Drummond 2007). To be consistent for all sites, minimum and maximum acceptable values were set at 1.88 and 17.57 Mg ha^{-1}, respectively, for maize and 0.31 and 3.77 Mg ha^{-1}, respectively, for soybean, and the standard deviation filter was set at 4 standard deviation intervals above or below the mean yield.

[1] Mention of tradenames does not imply endorsement by the University of Nebraska.

Table 1 Study locations and associated soil types, 2004 and 2005

Site ID	County	Year	Field size (ha)	Soil symbol	Soil name	Soil description
1	Merrick	2004 2005	31	Cg	Caruso-Gayville complex	Fine-loamy, mixed, mesic, Fluvaquentic Haplustolls
				Gc	Gayville-Caruso complex	Fine, montmorillonitic, mesic, Leptic Natrustolls
				Gg	Gibbon loam	Fine-silty, mixed (calcareous), mesic, Fluvaquentic Haplaquolls
				Jm	Janude sandy loam	Fine-silty, mixed, mesic Typic Haplaquolls
				Le	Leshara silt loam	Fine-silty, mixed, mesic Typic Haplaquolls
				Nv	Novina sandy loam	Coarse-loamy, mixed, mesic Fluvaquentic Haplustolls
2	Lincoln	2004	27	Lc	Lawet silt loam, drained	Fine-loamy, mixed, superactive, mesic Typic Calciaquolls
3	Chase	2004	55	Af	Altvan loam	Fine-loamy over sandy or sandy-skeletal, mixed, mesic Aridic Argiustolls
				Oaf	Otero-Canyon loams	Coarse-loamy, mixed (calcareous), mesic Ustic Torriorthents
				RtB/C	Rosebud-Canyon loam	Fine-loamy, mixed, mesic Aridic Argiustolls
				RsB	Rosebud loam	Fine-loamy, mixed, superactive, mesic Calcidic Argiustolls
4	Chase	2004	95	AsB	Ascalon fine sandy loam	Fine-loamy, mixed, superactive, mesic Aridic Argiustolls
				Gh	Goshen silt loam	Fine-silty, mixed, superactive, mesic Pachic Argiustolls
				RtB/C	Rosebud-Canyon loam	Fine-loamy, mixed, mesic Aridic Argiustolls
				TaB	Tassel-Duda loamy sands	Loamy, mixed (calcareous), mesic, shallow Ustic Torriorthents
				WpB	Woodly fine sandy loam	Fine-loamy, mixed, mesic Pachic Argiustolls
5	Merrick	2005	16	Cg	Caruso-Gayville complex	Fine-loamy, mixed, mesic, Fluvaquentic Haplustolls
				Gg	Gibbon loam	Fine-silty, mixed (calcareous), mesic Fluvaquentic Haplaquolls
				Jm	Janude sandy loam	Coarse-loamy, mixed, mesic Cumulic Haplustolls
				Nv	Novina sandy loam	Coarse-loamy, mixed, mesic Fluvaquentic Haplustolls

Data processing

Data interpolation

Aerial photographs of the study sites were re-sampled from 0.3 m × 0.3 m to 2 m × 2 m resolution by the nearest-neighbor method using ENVI 3.2 image analysis software (RSI—

Remote Sensing Exploitation Platform, Research Systems, Inc., Boulder, Colorado, USA). Pre-processed grain yield, EC_as, EC_ad, pH, NDVI and GNDVI data were imported into Surfer® 8.0 software (Golden Software Inc., Golden, Colorado, USA) and interpolated using the inverse squared distance method to a 10 m × 10 m grid with UTM (Universal Transverse Mercator) coordinates.

Statistical analysis

Linear and quadratic relationships between measured grain yield and data layers of EC_as, EC_ad, Veris pH, NDVI and GNDVI were examined using the general linear models (GLM) procedure (SAS v 9.1, SAS Institute, Inc., Cary, NC, USA). Regression analyses were done to determine the properties with the strongest relationship to yield, on a site-by-site basis as well as across all sites. This was followed by successive analyses to determine the layers with the second, third, fourth and fifth strongest relationships with yield. This was done site-by-site and across all sites, and was used to determine the relative value of including additional layers for predicting grain yield.

Management zone classification

Two layers (NDVI and EC_ad) were selected as having collectively the strongest relationship to grain yield across sites. Data from these two layers were used to delineate the management zones. To scale yield equally across sites and years, it was standardized to zero mean and unit variance (observed yield was subtracted from the annual mean, and then divided by the standard deviation) (Ferguson et al. 2003). These data were analyzed by the Management Zone Analyst software (MZA 1.0.1, University of Missouri-Columbia, Columbia, Missouri, USA) (Fridgen et al. 2004). The measure of similarity (Euclidean distance) and the fuzziness exponent (1.30) were left at the default values. Post classification analysis within MZA provided two performance indices, Normalized Classification Entropy (NCE) and Fuzziness Performance Index (FPI). The NCE determines the amount of disorganization created by dividing the data into classes (Lark and Stafford 1997) and FPI is a measure of membership sharing (fuzziness) among classes (Odeh et al. 1992). The best classification was determined when NCE and or FPI were at a minimum, representing the least membership sharing (FPI) or greatest amount of organization (NCE) as a result of the clustering process (Fridgen et al. 2004).

Results and discussion

Property selection

Grain yield is used as the primary indicator of the degree of chlorosis pressure in this study. Although many factors can influence yield potential, for these irrigated sites Fe chlorosis was the primary yield-limiting factor after water, nitrogen and phosphorus, which were applied at recommended rates. Soil Fe concentration is not a good predictor of the potential for pH-induced iron chlorosis, and plant tissue Fe concentrations do not indicate the presence or absence of pH-induced iron chlorosis accurately (Mengel 1994; Wallace et al. 1976). Observations made during the growing season confirmed that symptoms of iron

Table 2 Linear regression coefficients of mapped properties to grain yield—R^2

Parameter	Site 1 2004	Site 1 2005	Site 2	Site 3	Site 4	Site 5
pH	0.02	0.19	0.01	0.02	0.05	0
EC_as	0.01	0.50	0.03	0.36	0.09	0
EC_ad	0.01	0.53	0.02	0.33	0.25	0.01
NDVI	0.01	0.66	0.20	0.63	0.26	0.15
GNDVI	0.00	0.67	0.38	0.59	0.15	0.19
With inclusion of pH in model						
EC_as	0.02	0.51	0.04	0.36	0.11	0.00
EC_ad	0.02	0.53	0.03	0.33	0.25	0.00
NDVI	0.02	0.68	0.22	0.64	0.27	0.15
GNDVI	0.02	0.68	0.40	0.60	0.17	0.20
With inclusion of EC_as in model						
pH	0.02	0.51	0.04	0.36	0.11	0.00
EC_ad	0.01	0.54	0.03	0.36	0.28	0.02
NDVI	0.01	0.72	0.23	0.65	0.32	0.15
GNDVI	0.01	0.71	0.41	0.62	0.27	0.20
With inclusion of EC_ad in model						
pH	0.02	0.53	0.03	0.33	0.25	0.00
EC_as	0.01	0.54	0.03	0.36	0.28	0.02
NDVI	0.01	0.73	0.21	0.65	0.41	0.15
GNDVI	0.01	0.72	0.40	0.63	0.36	0.20
With inclusion of NDVI in model						
pH	0.02	0.68	0.22	0.64	0.27	0.15
EC_as	0.01	0.72	0.23	0.65	0.32	0.15
EC_ad	0.01	0.73	0.21	0.65	0.41	0.15
GNDVI	0.01	0.67	0.45	0.64	0.31	0.20
With inclusion of GNDVI in model						
pH	0.02	0.68	0.40	0.60	0.17	0.20
EC_as	0.01	0.71	0.41	0.62	0.27	0.20
EC_ad	0.01	0.72	0.40	0.63	0.36	0.20
NDVI	0.01	0.63	0.45	0.64	0.31	0.20

chlorosis were present in plants in areas of reduced yield. Table 2 gives the ability of each selected property to predict grain yield. The relationship of some properties to grain yield is relatively strong at sites 1 (2005) and 3, moderate for some properties at sites 2 and 4, and weak for most properties at site 5. Site 1 had non-existent relationships between properties and yield in 2004, but good relationships with most properties in 2005. Only a portion of the field was used for the study in 2004, whereas the entire field was used in 2005. Also, soybean was planted at site 1 in 2005 which is more sensitive to chlorosis pressure than maize, which was planted at site 1 in 2004. Across all sites, NDVI and GNDVI were found to be the two parameters most related to grain yield. In a second analysis, both linear and quadratic terms of NDVI and GNDVI were included in the model to determine which other properties have the next greatest ability to predict yield. Deep EC_a has the next greatest additional ability to predict yield across all sites after either

NDVI or GNDVI. In successive analyses, NDVI or GNDVI with EC_ad and their cross-products were included in the model to determine the third, fourth and fifth most important properties in predicting yield. Although other properties in the yield prediction model were statistically significant, this was due to the large number of observations at each site. Therefore, we decided that they did not substantially improve our ability to predict yield. Since GNDVI and NDVI, as well as EC_ad and EC_as, are auto-correlated, we investigated which combinations of these properties provided the most accurate prediction of yield. The combination of NDVI and EC_ad is the best combination of properties for predicting grain yield across all six sites, and in particular at sites 1 (2005) and 3. These were the two properties used in MZA to delineate chlorosis management zones.

Zone delineation

Sites 1 (2005) and 3 are the only two sites at which the NDVI-EC_ad model could predict yield with reasonable accuracy (Table 2). Figure 2 illustrates the relationship of chlorosis zones to grain yield for site 1 (2005). In general, the northern part of this field can be considered chlorosis-prone. This area generally coincides with the Gibbon loam (Gg) and Gayville-Caruso (Gc) soil series (Fig. 3). Both soil series are somewhat poorly drained, with salt accumulation in the Gayville series occasionally causing dispersion of the soil colloids (classified as Leptic Natrustolls). The relationship between the chlorosis zones and grain yield for site 3 is shown in Fig. 4. The chlorosis zones at this site are more scattered than for site 1 and show less coincidence with any specific soil series (Fig. 5). Figures 2–5

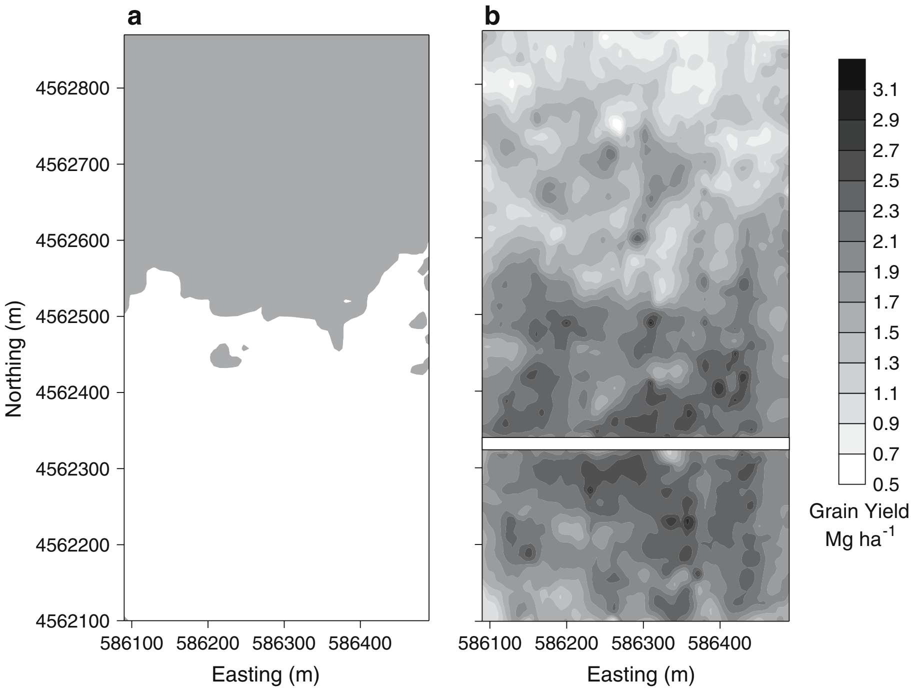

Fig. 2 Chlorosis-prone area (**a**) (zone 1, gray shading) delineated from the combination of EC_ad and NDVI, and soybean yield (**b**), site 1 (2005)

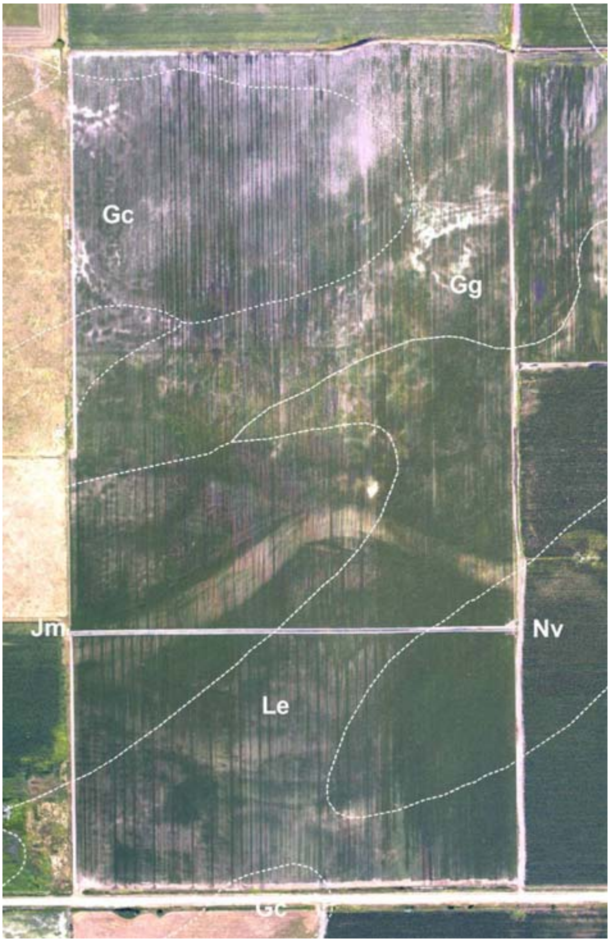

Fig. 3 Aerial photograph of site 1 (2005), with soil series boundaries superimposed

show that, for both sites, the chlorosis-prone zones coincided with visual observations of chlorosis during the growing season.

Table 3 gives mean values for properties within the chlorosis zones. Basing the delineation of chlorosis zones on the combination of NDVI and $EC_{a}d$ resulted in sites 1 (2004) and 5 having a slightly larger yield in the chlorosis-prone zone 1. At both of these sites there are no substantial differences in vegetation indices between zones. For site 1 in both 2004 and 2005, the chlorotic zone 1 has a slightly higher pH, and considerably larger EC_a at both depths, than the non-chlorotic zone 2. For site 2, soil pH and EC_a at both depths are only slightly higher for the chlorotic zone 1, with no difference in vegetation indices. For sites 3 and 4, pH is slightly higher for the chlorotic zone 1, but EC_a at both depths is larger for the non-chlorotic zone 2. Sites 3 and 4 are characterized by somewhat coarse and quite shallow soil. At these sites, larger EC_a indicates greater clay content and yield potential, compared to sites 1 and 5 where larger EC_a generally indicates salt accumulation because of poorly drained soil and thus a lower yield potential.

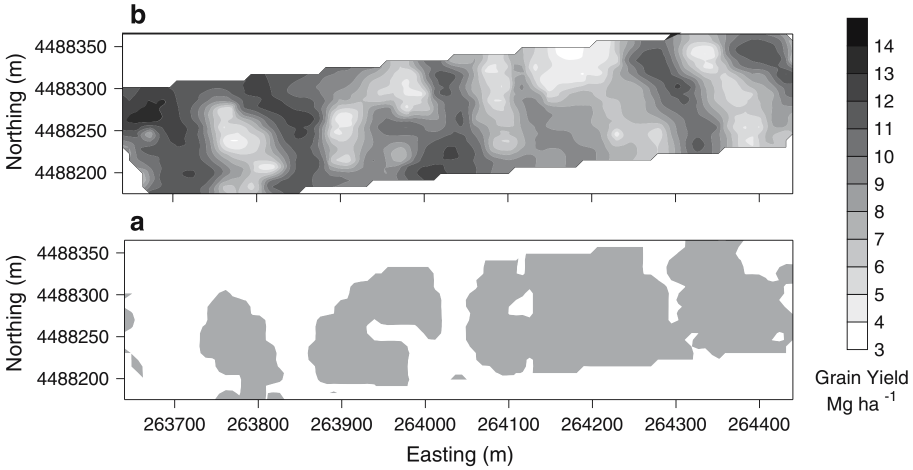

Fig. 4 Chlorosis-prone area (**a**) (zone 1, gray shading) delineated from the combination of EC_ad and NDVI, and maize yield (**b**), site 3

Fig. 5 Aerial photograph of site 3 with soil series boundaries superimposed. The study area is outlined with a solid line

Site 1 was planted with maize in 2004 and with soybean in 2005; the latter crop is more sensitive than maize to iron chlorosis. A larger part of the field was also used for the study in 2005. The more sensitive crop and greater area provided a strong relationship in 2005 between grain yield and chlorosis zones, while there was little relationship in 2004 between mapped properties and grain yield. However, chlorosis zones based on NDVI-EC_ad in 2004 showed a similar relationship to the zones mapped in 2005 (Fig. 6). This suggests that chlorosis zones might be stable across years, and could be a useful aid for improved management in future years.

Table 3 Mean values of mapped properties within delineated chlorosis management zones. Mean pairs with * are not significantly different ($p = 0.05$)

Site	Year	Zone	Yield ($Mg\ ha^{-1}$)	pH	EC_a shallow ($mS\ m^{-1}$)	EC_a deep ($mS\ m^{-1}$)	NDVI	GNDVI
1	2004	1	14.0	8.3	10.4	50.3	0.23*	0.27*
		2	13.8	7.8	3.7	18.8	0.23*	0.27*
1	2005	1	1.3	8.0	11.7	60.0	0.12	0.09
		2	2.1	7.7	4.6	25.3	0.24	0.17
2	2004	1	9.3	8.0	5.6	23.4	0.28*	0.29*
		2	9.9	7.9	5.1	20.5	0.28*	0.29*
3	2004	1	7.7	7.8	7.9	20.3	0.21	0.26
		2	10.3	7.7	10.5	27.1	0.26	0.29
4	2004	1	13.3	7.5	4.2	16.5	0.28	0.30
		2	14.2	7.3	5.9	22.3	0.30	0.31
5	2005	1	11.9	7.5	8.6	52.5	0.20	0.15
		2	11.8	7.4	3.5	19.4	0.18	0.14

Zone 1 is classified as chlorosis-prone

Site 1 planted to maize in 2004, soybean in 2005

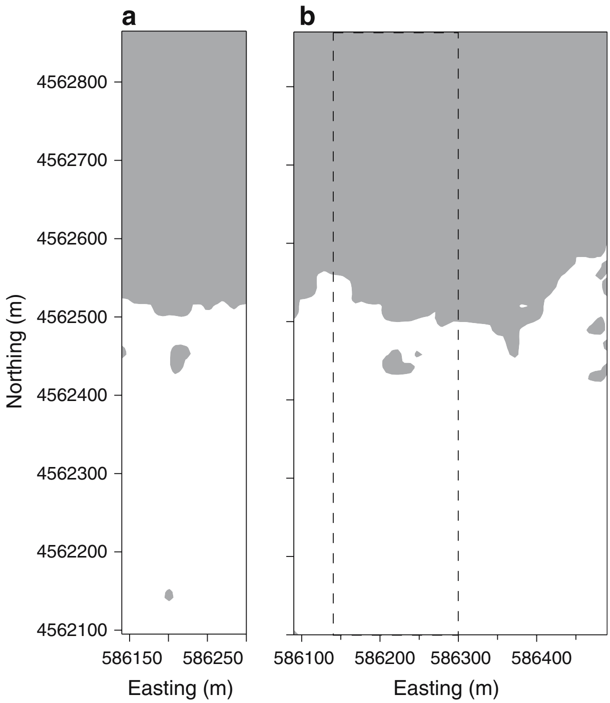

Fig. 6 Chlorosis-prone areas for site 1 (shaded gray): maize in 2004 (**a**), and soybean in 2005 (**b**), delineated from the combination of EC_ad and NDVI. The 2004 study area is shown with a dotted line

Economic considerations

The total area in site 1 (2005) is 30.8 ha. The area mapped as chlorosis-prone is 13.1 ha (42.7%), and 17.7 ha is mapped as not chlorosis-prone. Assuming a cost of \$69 ha^{-1} for a single soil application of 4.5 kg Fe ha^{-1}, Fe fertilizer application to the chlorosis-prone area of the field only would save $1221. This does not reflect any yield increase because of Fe application in the chlorosis-prone area of the field. For the study, 4.5 ha of site 3 is classified as chlorosis-prone (41.3%), whereas 6.4 ha is non-chlorotic. Applying Fe fertilizer only to the chlorotic-prone zone in the study area for site 3 would save $441. These analyses assume there would be no economic benefit from Fe fertilizer application to non-chlorotic areas of the field.

Conclusions

Two of the six sites examined in this study showed significant potential for the delineation of chlorosis management zones. At these sites, the combination of NDVI and EC_ad was the most useful for delineating chlorosis zones. Although the statistical relationship between the mapped properties and grain yield at site 1 (2004) was weak, chlorosis zones mapped based on NDVI-EC_ad were basically the same as those mapped the following year at the same site. The similarity in mapped zones for site 1 in 2004 and 2005 suggests that there is potential for chlorosis management zones to be useful for several years, but this needs to be evaluated at more sites and over longer time periods.

The economic impacts of knowing where management for chlorosis is appropriate can be significant. For example, assuming a cost of $69 ha^{-1} for a soil application of 4.5 kg Fe ha^{-1}, site-specific Fe fertilizer application for site 1 would save $1221, without accounting for any potential increase in yield with this application in chlorosis-prone areas.

Based on this study, we believe that sites 1 and 3 would be good candidates for site-specific chlorosis management practices. Two of the sites (sites 2 and 4) had moderate differences in properties between mapped zones and would be marginal candidates for site-specific chlorosis management, whereas site 5 had weak relationships between mapped properties and yield, and would not be a good candidate for site-specific chlorosis management. The combination of aerial imagery and soil EC_a information provides a good basis for delineating chlorosis-prone areas within fields. Although NDVI and GNDVI were the properties most significantly related to yield in this study, the combination of EC_ad with NDVI in the delineation process improved our ability to predict yield and insured that areas of reduced yield were associated with Fe chlorosis. Evaluation of site-specific chlorosis management on these and other sites is needed to investigate the agronomic and economic benefits of delineating chlorosis-prone zones.

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