Crop and soil based approaches for site specific nutrient management

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ABSTRACT

Recent precision agriculture research has focused on use of soil- (management zones) and crop-based (crop canopy reflectance determined with on-the-go sensors) methods for variable application of crop inputs such as N. The goal of our work is to show the advancements and applicability of these procedures in the United States and in Brazil obtained in collaborative research developed by ARS and Embrapa. Remotely sensed bare-soil images, elevation data, yield maps and soil electrical conductivity were used to categorize spatial and temporal field variability into management zones. A geo-referenced sampling scheme was designed to obtain soil chemical information for the zones. Stepwise multiple regression analysis was used to identify which indicators of the terrain were associated with spatial variation in crop yield. Elevation, soil color, slope, and soil electrical conductivity accounted for nearly 60% of the spatial variation in average yields, indicating that these variables could be useful when defining management zones. Since soil brightness was correlated with many of the terrain attributes, aerial photography would seem to be a promising method for developing management zones and obtaining important field information related to soil properties and crop productivity. However, because of wide variations in climate and its effect on spatial yield patterns, the management zone concept alone would appear inadequate for variable application of N inputs. A more successful approach would be to use a combination of soil-derived management zones along with the ability to practically monitor in- season crop N status and apply supplemental N as needed. Crop canopy reflectance sensors that measures reflectance at 550, 632, 600, 680 and 800 nm were used to assess chlorophyll status in corn (Zea mays, L.) growing under 5 N rates (0, 50, 100, 150 kg/ha and as needed defined by chlorophyll readings. The sensors are interfaced with a differential global positioning system (DGPS) to facilitate the generation of field reflectance maps. Results show that reflectance data converted into the green normalized difference vegetation index (GNDVI), utilizing the green and NIR bands was the most sensitive to assess variations in leaf chlorophyll content (assumed to be N status induced by varying levels of N application) and that variation in the sensor readings are highly correlated with ground-based chlorophyll meter readings. In the USA, the sensor was mounted on a high-clearance applicator for geo-referenced-on-the-go measurements in an irrigated cornfield. The mapping capabilities of the sensors indicate the potential to detect N stresses and subsequently direct localized application of variable rate N fertilizer. The sensor is robust in its operation and provides a number of data collection options and can be used under cloud conditions. However, significant efforts are still needed to deal with the soil background reflectance under incomplete ground cover situations and to determine the appropriate algorithms to translate sensor output into meaningful management options.

INTRODUCTION

Producers annually apply significant quantities of nitrogen (N) fertilizer to landscapes in the Corn Belt of the United States to achieve the typically high corn yields attained in the region. Nitrogen fertilizer is traditionally applied at uniform rates across fields as preplant or early-season side dress applications because of time and cost considerations. However, because of the spatial variability of most landscapes, not all areas in the fields require the same levels of N fertilizer. This results in some areas in a field receiving more N than the crop can use, leading to reductions in N use efficiency (NUE) and N losses. In fact, Raun and Johnson (1999) estimate NUE for world cereal grain production systems to be only 33%, with the unaccounted 67% representing a $15.9 billion annual loss of fertilizer N. Additionally, N losses results in environmental contamination through nitrate-N runoff or leaching, making nitrate-N the most common contaminant found in the surface and ground waters of the Corn Belt (CAST, 1999).

A major factor contributing to decreased NUE and environmental contamination for traditional N management schemes is the routine pre-season application of large doses of N, well before the time when the crop can effectively utilize this N. This stored N fertilizer is at significant risk to environmental losses as noted by Raun and Johnson, (1999). They point out that previous research has shown that NUE can be greatly improved by moving away from pre-season application and towards a greater emphasis on in-season applications of N fertilizer in amounts that better coincide with crop needs.

Previous work by Blackmer and Schepers (1994d), Blackmer et al. (1993) and Blackmer and Schepers (1995), using the Minolta SPAD 502 chlorophyll meter to monitor crop chlorophyll or N status and applying fertilizer N as needed, showed that crop-based approaches to manage N would be an improvement over traditional soil-based approaches. This work demonstrated, for example, that fertigation soon after detection of a crop N stress using a chlorophyll meter could maintain crop yields with less N fertilizer. Nitrogen stress and grain yield losses were observed to occur whenever chlorophyll meter readings for the "managed plots" declined below 95% of the meter values for reference strips receiving adequate to excess N at planting time.

They suggested that the 95% value (sufficiency index) would be a reasonable trigger point to apply additional fertilizer N. Subsequently, Varvel et al. (1997) confirmed these findings in a small plot study involving "as needed" N applications directed by chlorophyll meter assessments from early vegetative growth (V8) through silking (R2). Collectively, the research demonstrated 1) that the chlorophyll meter could be used as a research tool to maintain an adequate N supply for corn by fertilizing as needed and 2) that yields could be maintained with reduced N rates relative to a single preplant application of N. Our findings show that it is realistic for producers to move away from the uniform early season approach to N management and toward a more reactive approach involving crop evaluation and in-season N application (Schepers et al., 1992 Raun and Johnson, 1999). This approach should reduce the potential for soil N losses to the environment while simultaneously reducing farmer concerns over uncertain weather.

While research with the chlorophyll meter showed what could be accomplished regarding corn N management with small research plots, extrapolation of this concept to a whole field under center-pivot irrigation revealed that it would be difficult to collect enough chlorophyll meter data to characterize an entire field (Schepers et al., 1992). These findings clearly identified the need for technologies that would provide the same kind of information generated by a chlorophyll meter, but on a whole-field basis. Remote sensing - the process of acquiring information about objects from remote platforms such as ground-based sensors, aircraft, or satellites - is an option for obtaining information on crop N status of an entire field (Moran et al., 1997; National Research Council, 1997). This technique has been used by other scientists to characterize spatial variability in fields (Bhatti et al., 1991; Atkinson et al., 1992). The long-term goal of our research and others has been to develop a practical means of remotely sensing leaf chlorophyll levels.

Plants with increased levels of available N typically have greater leaf N concentrations, more chlorophyll (Inada, 1965; Al-Abbas et al., 1974; Wolfe et al., 1988), and greater rates of photosynthesis (Sinclair and Horie, 1989). Chlorophyll in leaves absorbs most strongly in the blue (around 450 nm) and red (around 670 nm), and reflects in the green (around 550 nm) regions of the spectrum. The Minolta SPAD 502 chlorophyll meter measures light transmission in the red (650 nm) and near-infrared (940 nm) parts of the spectrum to estimate leaf chlorophyll content (Blackmer et al., 1994d). The positive relationship between leaf greenness and crop N status means it should be possible to assess crop N needs from remotely sensed reflectance measurements of the crop canopy (Walburg et al., 1982; Hinzman et al., 1986; Dwyer et al., 1991) and leaves (McMurtrey et al., 1994).

However, there are technical concerns regarding the use of imagery data (satellite or aerial) for assessing canopy N status, particularly for canopies with incomplete closure and/or exposed soil. For example, Shanahan et al. (2001) collected aerial imagery data with a four-band [blue, green, red, and near-infrared (NIR)] digital camera system periodically through much of the growing season. They showed that reflectance in the green and NIR bands in the form of the GNDVI had greater potential for assessing canopy variation when collected after tasseling than before tasseling. This is because of the confounding effect of soil background in aerial imagery data collected before canopy closure. Other researchers have attempted to remove the soil background effect through mathematical manipulations of the various reflectance bands (i.e., soil-adjusted vegetative index, SAVI), but with limited success (Huete, 1988; Rondeaux et al., 1996; Baret et al., 1989). Thus, aerial imagery appears to have limited potential for use early in the growing season for evaluating crop N status, but later images, after canopy closure, hold more promise.

Technical problems, cost, reliability of using aerial imagery to evaluate crop N status, and the time lag between when data are collected and when they are available to make a management decision, have encouraged us to develop simple remote sensors that provide information on crop N status. One advantage of using real-time sensors over imagery is that the sensors can be positioned to minimize the potential for soil background in the field of view. We have finished an initial cycle of testing on an enhanced multispectral crop canopy reflectance sensor system, which when mounted on a high-clearance tractor is intended to operate as an in-season N applicator. By selecting the appropriate filters, the reflectance sensors can measure light reflected off the crop in various bands of the visible and NIR spectrum, which provide the greatest measure of difference between adequately fertilized and N-stressed corn canopies.

Recent research in precision agriculture has also focused on the use of management zones as a method to more efficiently apply crop nutrients, such as N, across variable landscapes. Management zones, in the context of precision agriculture, refer to geographic areas that possess homogeneous attributes in terrain and soil condition. Homogeneous attributes in a specific area should lead to similar crop yield potential, input-use efficiency, and environmental impact within that area.

Approaches to delineate management zones vary. Topography has been suggested as a logical basis to define homogeneous zones in agricultural fields (Franzen et al., 1998). This approach has been applied in Illinois and Indiana, where 40% of grain-yield variability was explained by topographical characteristics and selected soil properties (Kravchencko and Bullock, 2000). Aerial photographs, crop canopy images, and yield maps have also been suggested as guides for delineating management zones (Schepers et al., 2000a). Remote sensing technology is especially appealing to identify management zones, because it is noninvasive and low cost (Mulla and Schepers, 1997). Additionally, scientific evidence for suggesting practical use of remote sensing technology to delineate management zones is increasing (Varvel et al., 1999). Another promising noninvasive approach to define boundaries of management zones involves use of magnetic induction to measure soil EC. This approach has been used to effectively map variations in surface soil properties such as salinity, water content, and percent clay (Sudduth et al., 1998) and characterize soil variability due to texture, depth to sand, claypans, other buried features, (Doolittle et al., 1994; Kitchen et al., 1996) and variations in carbonates, soil organic matter, and soil erosion state (Johnson et al., 2001). Magnetic induction has also been used to track soluble nutrient levels in soil (Eigenberg et al., 2001). Caution is necessary when using this approach because of the extreme sensitivity to soil type and management conditions, but its ease of use makes it an attractive tool for precision farming applications (Lund et al., 1998). Yield mapping is yet another approach to delineate management zones. This approach is considered to be the primary form of precision agriculture technology in the United States (Pierce and Nowak, 1999). However, practical application of yield mapping to identify zones has been plagued by year-to-year variation in the maps (Huggins and Alderfer, 1995; Sadler et al., 1995). For example, Eghball and Varvel (1997) found that temporal variability was much more dominant than spatial variability for corn grain yields in eastern Nebraska, implying that temporal variability may greatly influence how spatial variability is expressed in a given field. Hence, it seems unlikely that the static management zone concept alone will be adequate for using N more efficiently. Alternatively, our proposed strategy will combine the use of management zones with crop-based in-season remote sensing systems to apply N more efficiently.

> The objective of these studies conducted in both the United States and in Brazil were to 1) evaluate approaches to delineate management zones and 2) compare the performance of canopy reflectance measured with a multi-spectral reflectance sensor system to variations in leaf chlorophyll concentration determined with a Minolta (model SPAD 502) chlorophyll meter.

MATERIALS AND METHODS

Management Zones

US Site

The study was conducted on a center-pivot irrigated field located near Gibbon, Nebraska (40° 53' 27 N, 98° 51' 37 W, 640 m above m.s.l.), representing approximately 53 ha. The field has been planted continuously to corn since 1990, using ridge-till methods. The topography is rolling with approximately 30 m of relief (Fig. 1), and three soil series are present in the field

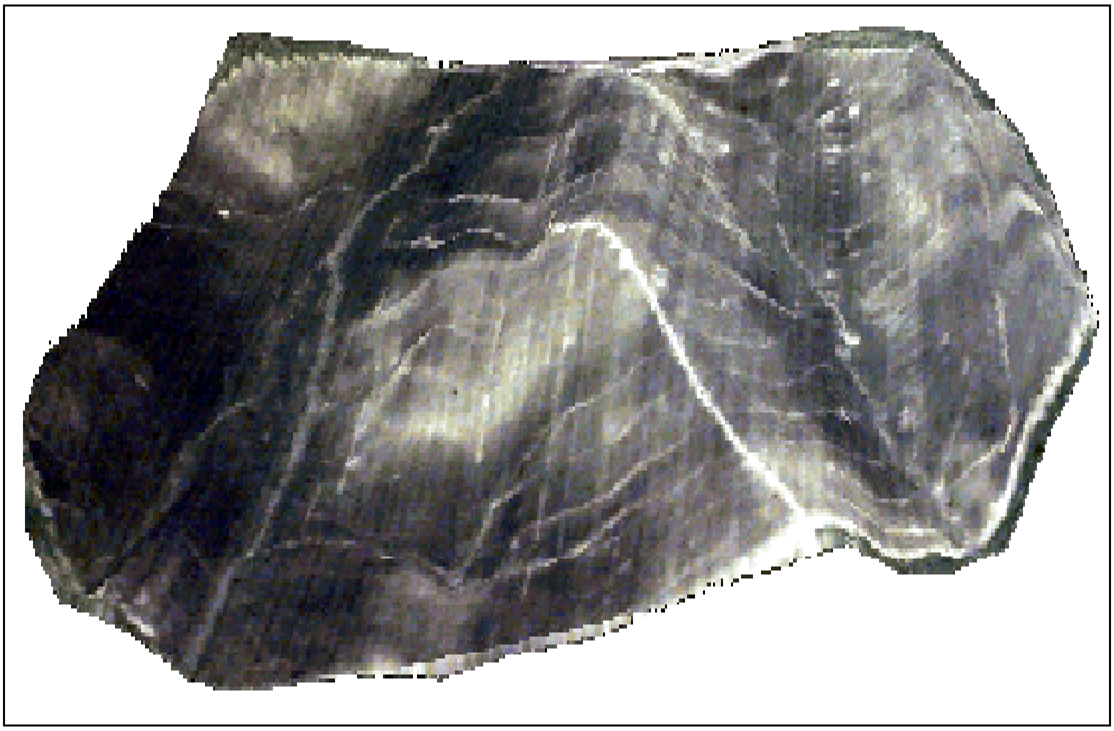


Figure 1. Bare soil image overlain onto three-dimensional surface contour of the field depicting a combination of soil color and topography variation.

An aerial photograph of the bare soil surface was acquired during the spring of 1999, using an aircraft mounted 35 mm camera equipped with Kodak Ektachrome color film. The aircraft was flown at the altitude of approximately 2,130 m during image acquisition. Prior to image acquisition, five targets (white-painted 1.2 x 2.4 m wood sheets) were placed in the center and perimeter of the field area. Geological coordinates were obtained for the targets with a DGPS receiver for use in the image georegistration process. The 35 mm color slide was scanned, inputted into Imagine GIS software (ERDAS, Atlanta, GA), geo-referenced, and processed as brightness values for blue, green, and red. The brightness values were used to develop three computer-generated management zones.

Prior to planting the 1999 crop, a geo-referenced soil-sampling scheme was used to characterize soil chemical properties at different points within each management zone. Within a 10 m radius of each sampling point, twenty soil cores were collected to a 30 cm depth and composited. A total of 47 points in the field were sampled. Samples ere analyzed for soil electrical conductivity and pH (1:1 soil-water ratio), NO_3-N and NH_4-N (cadmium reduction followed by a modified Griess-Ilosvay method), extractable P (sodium bicarbonate extraction), and soil organic matter (estimated from soil organic carbon).

Soil electrical conductivity was mapped using an electromagnetic induction EM38 ground conductivity sensor (Geonics Ltd, Ontario, Canada). The sensor uses electromagnetic energy to measure the apparent conductivity of earthen materials. The sensor was mounted on a nonmetallic cart, 36 cm above the soil surface, and pulled (6 km/h) through the field with a truck following parallel swaths at 20 m intervals. The sensor was operated in the vertical mode, which measured an effective soil layer of 0-90 cm. Conductivity data were geo-referenced using a DGPS receiver mounted on the top of the truck cab. Data were collected at one-second intervals and stored in a data logger. Elevation data obtained from the DGPS receiver were used to determine terrain attributes.

The field was yield mapped for the seasons of 1997, 98, 99, 2000, 01) with a John Deere 9600 combine (12-row corn head) equipped with a Green Star yield monitoring system. Data for yield, moisture, and geo-coordinates were recorded every second. Yield data were processed and mapped with Farm HMS software (Red Hen Systems, Fort Collins, CO).

Imagine software (ERDAS, Atlanta, GA) was used to develop interpolated layers from data points for soil color brightness, elevation, electrical conductivity, and grain yield. Inverse distance weighting was used as an interpolation method for creating maps, with maps consisting of 15 m grids. Elevation measurements were converted into grid-based estimates of terrain, slope, and aspect. Slope describes the rate of elevation change, and is defined as the first-order derivative of elevation. Aspect identifies the steepest down-slope direction from each cell to its neighbors. The values of the output grid theme represent the compass direction of the aspect; 0 is true north, a 90-degree aspect is to the east, and so forth.

Simple correlation analysis was used to determine association between grain yield and various terrain attributes. Multiple stepwise regression analysis was used to assign relative importance of terrain attributes to grain yield.

Brazil Site

The study in Brazil was conducted on a soybean rain-fed field located near Sidrolândia, MS representing approximately 115 ha. Part of the field has been

planted in a soybean-corn-barley rotation since 1987, using no-till methods and part was planted with soybean last year, after being under pasture (Brachiaria, sp) for thirteen years. The native vegetation is savanna (cerrado), the topography is suave rolling and the soil is a Red-Dark Latosol with 20% of iron oxide.
Soil electrical conductivity was mapped using a colter-based sensor-cart (Veris Model 3100) Lund & Christy 1998. A pair of coulter electrodes transmits an electrical current into the soil, while two others pairs of electrodes measure the voltage drop. Geo-referenced data were collect on a 1 s interval.

The field was yield mapped for the season of 2001 with a Massey Ferguson combine equipped with a Field Star yield monitoring system. Data for yield, moisture, and geo-coordinates were recorded every second. Yield data were processed and mapped with Farm HMS software (Red Hen Systems, Fort Collins, CO).

RESULTS AND DISCUSSION

Soil Approach - Management Zones

US Site

The US site exhibited considerable variability in soil color and topographical relief (Fig. 1). The darker-colored (less reflective) soil is located in the lower regions of the field, whereas, the lighter-colored soil is more prevalent on the upland locations. The bare-soil color image was used to produce the computer-generated management zones, resulting in three distinct regions.

The sampling scheme generated by computerized analysis of soil color revealed distinctly different soil chemical properties for these three zones (Table 1). For example, we detected an almost two-fold increase in SOM levels for the darker soil at lower elevations versus the lighter soil at higher elevations (blue color). Our results, regarding the association between elevation and SOM, are consistent with the observations of Kravchenko and Bullock (2000). Other indicators of crop productivity potential such as soil EC, pH, NO_3-N, NH_4-N, and P also indicated that the lowland dark soils were more fertile than the upland lighter soils. Soil brightness, an indirect indicator of SOM (Varvel et al., 2000), was positively associated with elevation in our work.

Table 1. Soil chemical properties for the three management zones.

		EC$_{1:1}$	pH	SOM	NO_3-N	NH_4-N	P
Zone	*N*	(dS m^{-1})		%	-------------kg/ha----------------		
Blue	18	0.42	7.37	0.94	7.7	6.0	13.2
Purple	19	0.28	6.48	1.31	10.2	8.3	27.5
Cyan	10	0.24	6.17	1.68	17.0	2.9	68.9

The soil EC map (Fig 2) revealed patterns similar to the soil color and management zone map (Fig 3). Low EC values were found with the lowland dark-colored soils, while higher EC values are found at the light-colored upland areas where erosion has been most severe. Since this soil possesses calcareous subsoil, eroded areas would be expected to have higher carbonate levels resulting in higher pH and EC values, as is shown in Table 1.

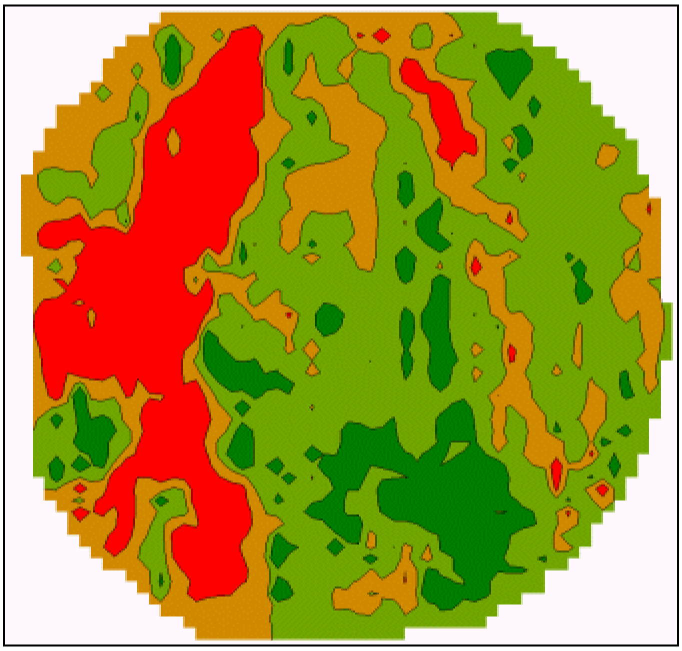


Figure 2. Soil electrical conductivity map from center pivot irrigated cornfield (red < 0.304, brown = 0.304-0.324, light green = 0.324-0.343, green = >0.343 dS m^{-1}).

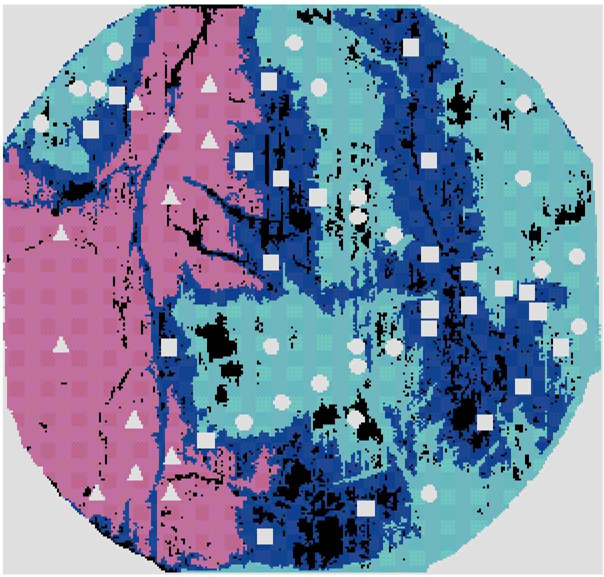
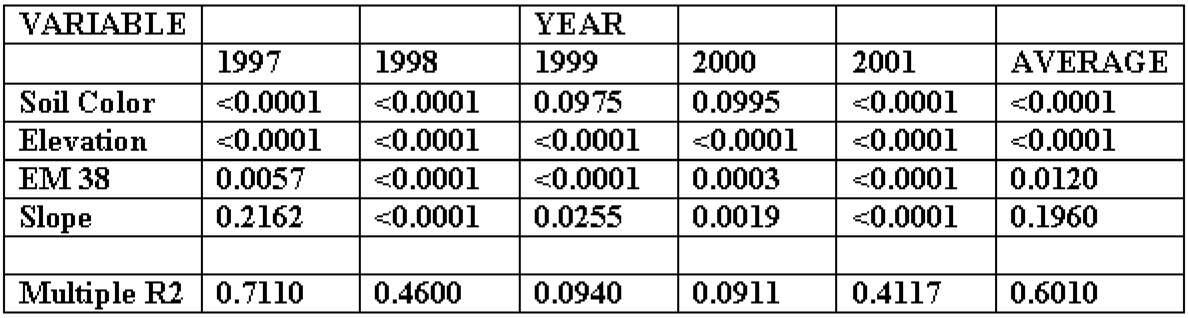


Figure 3. Soil management zones (Blue - zone 1; Purple - zone 2; Cyan - zone 3) and soil sampling scheme.

The yield maps showed both spatial and temporal variation in grain yields for the 1997-98 -99-2000-01 growing seasons. Except for 1999 and 2000, the spatial yield patterns showed good resemblance with the delineated management zones.
Table 2 shows the temporal soil properties effects on the yield. Multiple regression analysis revealed that on average elevation, soil color, slope, and EC attributes accounted on average for nearly 60% of the variability in grain yield. It also shows that the effects of these attributes change year by year.

Table 2. Association between spatial variation in terrain properties and spatial variation in grain yield as determined by stepwise regression analysis.



VARIABLE			YEAR			
	1997	1998	1999	2000	2001	AVERAGE
Soil Color	<0.0001	<0.0001	0.0975	0.0995	<0.0001	<0.0001
Elevation	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
EM 38	0.0057	<0.0001	<0.0001	0.0003	<0.0001	0.0120
Slope	0.2162	<0.0001	0.0255	0.0019	<0.0001	0.1960
Multiple R2	0.7110	0.4600	0.0940	0.0911	0.4117	0.6010

Since soil brightness was correlated with many of the terrain attributes, aerial photography would seem to be a promising method for developing management zones and obtaining important field information related to soil properties and crop productivity.

Brazil Site

Measurement of the soil electric conductivity could discriminate different areas in the terrain (Fig 4). Information obtained from the farm owner about the past management of the area, associated with a soybean yield map from 2001 crop season indicate an agreement between soil EC and grain yield.

Based on these facts a soil-sampling scheme was established targeting four different zones. Interpreting the physical and chemical properties shown on table 3., it can be said that the form in which the soil management is the main cause of variation in the EC values. Since this Oxisol has a very low natural fertility, the lime and the fertilizer applied to meet the crop requirements has increased the content of the elements specially Calcium and Nitrate that have a direct effect on EC values. Zone 1, which has been cropped under no-tillage for fifteen years, has adequate fertility level with high values of SEC. Zone 4 was a corral and the high values of SEC is a consequence of the nitrate and calcium contained in the manure. Zones 2 and 3 were covered with pasture with almost no fertilizer applied and have quite similar soil chemical properties. However, this division happened as a function of the grouping patterns of the SEC values. Since the soil texture is quite homogeneous it can be inferred that SEC seems to have the potential to be used as a proxy indicating the soil fertility levels.

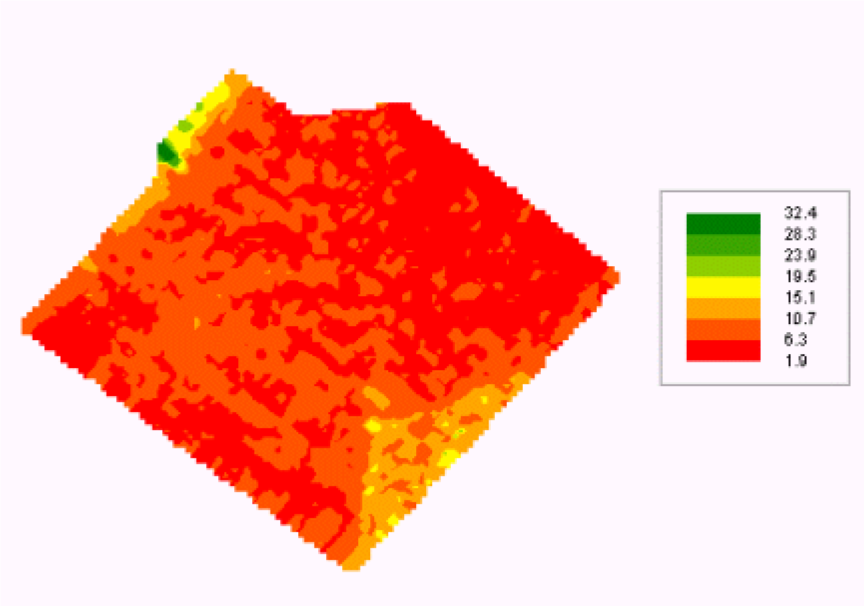


Figure 4. Soil Electrical Conductivity (mS/m)of a Dark-Red Latosol at Sidrolândia, MS.

Crop Approach - Canopy Sensors

US Study Site

Data collected with this sensor system during 2000 from small plot research at the MSEA site are encouraging. Results show that the 550 nm wave band was the most sensitive to assess variations in leaf chlorophyll content (assumed to be N status induced by varying levels of N application) and that variation in the sensor readings are highly correlated with ground-based chlorophyll meter readings. These findings suggest the sensor is capable of detecting variations in leaf chlorophyll or N status induced by varying levels of N application, since variation in the sensor readings (expressed vegetation index) was highly correlated (r_2 =0.8914) with ground-based chlorophyll meter readings for plants measured at the V 11 growth stage. In the USA, the sensor was mounted on a high-clearance applicator for geo-referenced-on-the-go measurements in an irrigated corn-field. The mapping capabilities of the sensors indicate the potential for them to detect N stresses and subsequently direct localized application of variable rate N fertilizer. Ideally, the amount of N applied would depend on: the crop growth stage, mineralization potential of soil, yield goal, etc. The sensor is robust in its operation, provides a number of data collection options and it can be used under cloud conditions. However, significant efforts are still needed to deal with the soil background reflectance under incomplete ground cover situations and to determine the appropriate algorithms to translate sensor output into meaningful management options.

Final Considerations

The goal of our work was to determine the capacity of terrain information, aerial photographs, magnetic induction, and yield mapping to effectively delineate management zones. For an irrigated cornfield near Gibbon, NE, elevation, soil color, aspect, slope, and soil electrical conductivity accounted for nearly 60% of the spatial variation in yield, indicating that these variables could be useful when developing management zones. This approach was also very effective in Brazil and served as a template for directed soil sampling schemes to characterize soil properties known to affect crop yield.

The mapping capabilities of the sensors indicate the potential for them to detect N stresses on-the-go and to make in-season nitrogen applications.

A combination of the information could obtained by the two approaches, crop and soil, could provide a more economical means for variable application of crop inputs.

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