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# 8 Site-specific management and delineating management zones

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## Introduction

Conventional agriculture has served humankind well. However, the limitations of conventional agricultural practices are becoming increasingly evident as the world's food producers push production to the limit with finite resources and the public closely scrutinizes the environmental ramifications of producers' efforts. Because conventional agriculture disregards the spatial and temporal complexity of the interacting factors that affect crop yield and focuses on productivity, it will not be able to meet the global economic, environmental and limited-resource challenges of the future. Barring any new technological breakthroughs, precision agriculture, or, more specifically, site-specific crop management, is the next logical step to meet world food demands using state-of-the-art scientific knowledge and technology that can address these spatial and temporal complexities.

### *Factors responsible for within-field crop-yield variation*

Ever since the classic paper by Nielson *et al.* (1973) concerning the variability of field-measured soil water properties, the significance of within-field spatial variability of soil properties has been scientifically acknowledged. However, until recently, with the introduction of global positioning systems (GPS) and yield-monitoring equipment, documentation of crop yield and soil variability at the field scale was difficult to establish. Now there is well-documented evidence that spatial variation within fields is highly significant and amounts to a factor of 3–4 or more for crops (Birrel *et al.*, 1995; Verhagen *et al.*, 1995) and up to an order of magnitude or more for soil (Corwin *et al.*, 2003a).

Spatial variation in crop yield is the result of a complex interaction of edaphic (i.e. soil-related, such as salinity, organic matter, nutrients, texture), biological (e.g. disease, pests, earthworms, microbes), anthropogenic (e.g. irrigation management, leaching efficiency, soil compaction due to farm equipment), topographic (e.g. slope, elevation, aspect) and meteorological (e.g. relative humidity, temperature, rainfall, wind) factors. All of these factors vary spatially, but some vary both temporally and spatially, resulting in complex spatial patterns that cannot be measured with fixed sensors or a single plant or soil sample.

### *Conventional versus site-specific management*

Although it is well known that soil is spatially heterogeneous, conventional farming currently treats a field uniformly with respect to the application of fertilizer, planting density, pesticides, soil amendments, irrigation water and other inputs, which ignores the naturally inherent variation in soil and crop conditions between and within fields. Conventional agriculture, therefore, inherently under- or over-applies inputs such as irrigation water, fertilizer, pesticides and soil amendments in some parts of fields. Failure to address within-field temporal and spatial variation in edaphic properties, as well as variation in anthropogenic, biological, meteorological and topographical factors that affect crop yield, has detrimental effects on economic benefits because of reduced yield in certain areas of a field and on the environment because of over-applications of agrochemicals and water, which is a waste of finite resources. This costs the producer and the public money, depletes finite resources and degrades soil, surface-water and groundwater resources.

In contrast to conventional agriculture, site-specific crop management, or more simply site-specific management (SSM), attempts to manage soil, pests and crops based upon spatial variation within a field (Larson and Robert, 1991). Site-specific management is a form of precision agriculture where decisions on resource application and agronomic practices closely match crop requirements as they vary within a field; consequently, the collective actions are differential rather than uniform. The aims of SSM are to apply inputs (e.g. irrigation water, fertilizer, pesticides, soil amendments, etc.) *when*, *where* and in the *amount* needed to optimize crop yield.

### *Need for site-specific management*

Although total yields continue to rise on a global basis, there is a disturbing trend, with some major crops such as wheat and maize that are reaching ‘yield plateaus’ (World Resources Institute, 1998). The prospect of feeding a projected additional 2–3 billion people over the next 30–40 years poses greater challenges than those faced over the past 30–40 years because of finite resources. In addition there are impacts on the environment that result in unsustainability, changes in climatic conditions that threaten agriculturally productive regions and increased water scarcity. It is unlikely that conventional agriculture can solve these challenges.

In an effort to feed the world population, conventional agriculture has affected the environment detrimentally with the loss of natural habitat, use and misuse of pesticides and fertilizers, and degradation of the soil and water resource. By 1990, poor agricultural practices had contributed to the degradation of 38 per cent of the roughly 1.5 billion ha of crop land worldwide and since 1990 the losses have continued at an annual rate of 5–6 million ha (World Resources Institute, 1998).

Sustainable agriculture is regarded as the most viable means of meeting the food demands of the world’s growing population because its aim is to optimize profitability, productivity, sustainability and use of resources and reduce environmental impacts. Site-specific management is the most promising means of attaining sustainable agriculture because it addresses the weaknesses of conventional agriculture, namely spatial and temporal variation.

## Components of site-specific management (SSM)

A site-specific management system consists of five fundamental components: (1) spatial referencing; (2) measurement and monitoring of crop, soil and environmental attributes; (3) attribute mapping; (4) decision support system (DDS); and (5) differential action. The technologies to bring SSM into its own fell into place in the mid 1990s, particularly with the maturation of global navigation satellite systems (GNSS), in situ and on-the-go sensor technologies, geographic information systems (GIS) and variable-rate technology (VRT).

Spatial referencing links data to a specific coordinate location on the Earth's surface. Global navigation satellite systems, such as the Global Positioning System (GPS), are the technology that has made geo-referencing possible with accuracy from several metres to sub-metre. Geo-referencing from GNSS made it possible to provide accurate location information that is crucial for sensor technology, GIS and VRT. In addition, geo-referencing has provided producers with (1) a navigation aid known as parallel tracking, which allows farm equipment operators to visualize their position with respect to previous passes; (2) auto-guidance to steer agricultural vehicles automatically with occasional oversight by the operator; and (3) autonomous vehicles where the operator's presence is not required, allowing for the safe application of farm chemicals that are hazardous to human health.

A variety of sensors and monitors is needed for SSM to measure various crop, soil, landscape and environmental variables. These in situ and on-the-go sensors include sensors for crop yield and quality; crop reflectance for biomass, vigour and stress; soil attributes of apparent electrical conductivity ($EC_a$), reflectance, pH and natural gamma radiation emission; and elevation. With the spatial referencing capabilities of GNSS, geo-referenced attributes of crop, soil and relief are gathered from direct sensor measurements (e.g. pH, yield and elevation) or from sensor-directed soil sampling (e.g. $EC_a$-directed soil sampling). Yield monitoring and mapping refers to the collection of geo-referenced data on crop yield and crop characteristics, such as moisture content, while the crop is being harvested. Similarly, elevation data for a field can be recorded during planting, cultivation or harvesting using real-time kinetics (RTK) GPS equipment to provide horizontal and elevation measurements at centimetre accuracy, which are useful in auto-steering, strip tillage, drainage and digital elevation mapping (DEM). The on-the-go measurement of pH using the Veris pH Manager (Veris Technologies, Salinas, KS) is a sensor technology that is growing rapidly for variable-rate liming of field areas where pH is too low or for application of sulphur to areas that are too alkaline for the crop. Geo-referenced measurements of $EC_a$ with electrical resistivity (e.g. Veris 3100)* or electromagnetic induction (e.g. Geonics EM38

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* All product identification is provided solely for the benefit of the reader and does not imply endorsement by the USDA.

and DUALEM-2) have been used to map a combination of soil properties that potentially influence crop yield. Apparent soil electrical conductivity sensors are sensitive to soluble salts (i.e. salinity), clay, water content, organic matter and bulk density; consequently, the $EC_a$ measurement is a complex combination of all these properties. Because of its complexity, geo-spatial $EC_a$ measurements are used to direct soil sampling to reflect the range and variability of those soil properties that predominantly influence $EC_a$ in a particular field. By applying statistical sampling designs to geo-referenced $EC_a$ measurements, including design-based sampling (e.g. random sampling, stratified random sampling, unsupervised classification, etc.) or model-based sampling (e.g. response surface sampling), sample locations are established that will reflect the range and spatial variation of those soil properties correlated to $EC_a$ for that field. Directed sampling using $EC_a$ is the most widely used approach for characterizing the spatial variation of soil properties (Corwin and Lesch, 2005a). Arguably, sensors that measure $EC_a$ provide the widest range of spatial information for SSM because $EC_a$ is influenced by several soil-related properties. This is often the case when $EC_a$ correlates with crop yield. However, in dryland agriculture $EC_a$ often does not correspond to yield-limiting factors. In these cases, a strong argument can be made that crop sensors will provide the most useful information, whereas $EC_a$ sensors will usually excel for irrigated agriculture on arid and semi-arid soils. This is clearly demonstrated by the ability of $EC_a$-directed sampling to provide salinity and texture maps that allow for the separation of osmotic (i.e. salinity) and matric (i.e. water content) potential effects of salt-affected soils on crop yield, which is not possible with crop sensors.

Remote sensing is also one of the more common sensor technologies used in SSM. Remote sensing is defined as the acquisition of data about an object without being in physical contact (Elachi, 1987). Satellite imagery (e.g. Landsat 5 and Landsat 7; SPOT) provides multispectral images, where the normalized differential vegetative index (NDVI) bands have been used successfully to identify soil factors that affect crops and also the nutrient status of crops. However, the remote-sensing systems most common to agricultural applications are from airborne systems, which produce images with more detailed resolution than Landsat or SPOT images. There are also handheld optical sensors that belong in the remote-sensing category. Handheld sensors provide the advantage of ease-of-use and of allowing measurements to be taken at a time of the user's choosing, with high resolution.

The temporal and spatial data from sensors result in extremely large datasets, therefore computer software that can compile, organize, manipulate and display attributes as maps is needed. This software is referred to as a geographic information system. A variety of commercial GISs are available; the most common of which is ESRI's ArcGIS. The current GIS software is capable of overlaying data layers (e.g. permeability, salinity, water content, clay, nitrates, pH, etc.) and of performing sophisticated spatial analysis of data that includes geostatistical techniques such as kriging or co-kriging and deterministic techniques such as inverse distance weighting and global polynomial interpolation, to mention a few. All of these capabilities of a GIS are useful in creating digital maps for SSM.

In general terms, a DSS is an information system that supports decision-making. A DSS in the context of SSM provides the means to examine the temporal and spatial variation in crop growth and yield to formulate differential actions. From a DDS, areas are established where unique treatment is needed. These areas of unique treatment are referred to as site-specific management zones or site-specific management units (SSMUs). Site-specific management units provide information on where and how much action is needed, and are regions within a field that have a relatively homogeneous combination of yield-limiting factors for which a single rate of a specific input is appropriate. Variable-rate application and variable-position technologies for the differential management of fertilizers, irrigation, pests, soil amendments and plant density use the information from SSMUs to meet optimized goals of profitability, productivity, use of resources and environmental impact.

Site-specific management units may or may not be temporally and spatially stable. An example of a temporally unstable SSMU is one that delineates an area of an irrigated field where a soil amendment, such as gypsum, is added to reduce large concentrations of Na on exchange sites as a means of improving permeability. The SSMUs will become irrelevant once site-specific applications of gypsum reduce Na levels sufficiently and increase permeability to an acceptable level. In contrast, plant available water is predominantly influenced by texture, which from an agricultural perspective is temporally stable; consequently, SSMUs for irrigation to meet plant available water needs are generally temporally and spatially stable.

To manage within-field variability site-specifically, geo-referenced information about relevant characteristics for crop production must be available. The technology for SSM is available now, but information on spatial and temporal variation is often inadequate (van Uffelen *et al.*, 1997). Yield maps provide information on the integrated effects of physical, chemical and biological processes under certain weather conditions (van Uffelen *et al.*, 1997), and provide the basis for implementing SSM by indicating where crop inputs need to be varied based upon spatial patterns of crop productivity (Long, 1998). However, the inputs necessary to optimize crop productivity and minimize environmental impacts can be derived only if the factors that gave rise to the observed spatial crop patterns are known (Long, 1998). Yield maps alone cannot provide sufficient information to distinguish between the various sources of variability, and cannot provide clear guidelines without information on the effect of variability in the weather, pests and diseases, and soil physical and chemical properties on crop yield and quality for a particular year (van Uffelen *et al.*, 1997). Each factor that affects the within-field variation in yield needs to be characterized spatially to be able to manage a crop on a site-specific basis. For this reason researchers are currently evaluating multi-sensor platforms that can provide a full spectrum of geo-referenced data for soil, crop and environment.

## Delineating site-specific management units (SSMUs)

An important aspect of SSM is the delineation of site-specific management units (SSMUs). Determination of SSMUs is difficult as a result of the complex combination and interaction of factors that influence crop yield. Ideally, an SSMU will account for the spatial variation of all factors that affect the variation in crop yield, including edaphic, meteorological, biological, anthropogenic and topographic factors, and will optimize productivity, profitability, sustainability, resource utilization and environmental impacts. This has not yet been achieved completely. However, SSMUs have been defined based on edaphic and anthropogenic factors derived from $EC_a$-directed soil sampling (Corwin *et al.*, 2003b; Corwin and Lesch, 2005a), soil-type surveys and map overlays of topsoil depth and elevation (Kitchen *et al.*, 1998), topographic attributes and landscape position data to map productivity based on plant available water (Jones *et al.*, 1989; Jaynes *et al.*, 1994; Sudduth *et al.*, 1997) and soil fertility (Khosla *et al.*, 2002; Chang *et al.*, 2004), to mention a few.

In most instances, the delineation of SSMUs relied on crop and soil proximal sensors to establish crop inputs that are commonly applied using VRT. Common crop inputs applied using VRT include nutrients (N, P and K), manure, lime, gypsum, seeding rate, herbicides, pesticides and irrigation water. Site-specific management units have been established for each of these crop inputs using a variety of different factors. For instance, P and K management zones have been established from topography, grid or directed soil sampling, soil survey maps and $EC_a$ maps. Manure and N management zones have been derived from soil texture, organic matter, yield patterns, bare soil photos, $NO_3$_N and crop canopy reflectance. Lime management zones have come from soil pH and soil texture, while gypsum management zones have come from grower knowledge, yield patterns, $EC_a$ maps and soil tests for pH and Na. Seeding-rate management zones have been based on historical yield maps and topsoil depth. Herbicide management zones have been derived from weed maps, soil organic matter and soil texture; and pesticide management zones have been derived from soil properties. Site-specific irrigation management units have been established from soil texture, topography, yield zones and $EC_a$-directed soil sampling.

## Crop and soil proximal sensors for delineating SSMUs

Ground-based proximal sensors are sensors that take measurements from within a distance of 2 m from the soil surface. They may take measurements of the soil, such as electrical, electromagnetic or radiometric sensors, or of plants, such as crop yield or spectral sensors. Proximal sensors are of particular importance to site-specific management because they can obtain large volumes of reliable spatial and temporal data of soil and plant properties at relatively low cost and labour input.

Adamchuk *et al.* (2004) categorized proximal sensors into six categories: (1) electrical and electromagnetic; (2) optical and radiometric; (3) mechanical; (4) acoustic; (5) pneumatic; and (6) electrochemical. Numerous review and technical papers have been prepared dealing with proximal sensors, with just a few of the more current ones listed in Table 8.1. Each sensor is typically affected by more than one agronomic property. Table 8.2 outlines the agronomic properties influencing each category of proximal sensor.

*Table 8.1* Selected recent references using proximal soil sensors to map soil properties for applications in precision agriculture (modified from Adamchuk *et al.* 2004)

| *Category of proximal sensor* | *Review article* | *Sensor* | *Technical reference* |
|---|---|---|---|
| Electrical and EMI | Corwin and Lesch (2005a) | ER<br>EMI<br>Capacitance | Corwin *et al.* (2003b)<br>Corwin and Lesch (2005b, 2005c)<br>Andrade *et al.* (2001) |
| Optical | Ben-Ddor *et al.* (2009)[a] | Single wavelength<br>Multi- or Hyperspectral | Shonk *et al.* (1991)<br>Maleki *et al.* (2008), Mouazen *et al.* (2007) |
| Radiometric | Huisman *et al.* (2003) | GPR<br>Microwave | Lunt *et al.* (2005)<br>Whalley and Bull (1991) |
| Mechanical | Hemmat and Adamchuk (2008) | Draft<br>Load cells and penetrometers | Mouazen and Roman (2006)<br>Chung *et al.* (2003), Verschoore *et al.* (2003) |
| Acoustic and pneumatic | | Microphone<br>Air pressure transducer | Liu *et al.* (1993)<br>Clement and Stombaugh (2000) |
| Electrochemical | | ISFET<br>ISE | Birrell and Hummel (2001)<br>Adamchuk *et al.* (2005), Sethuramasamyraja *et al.* (2008) |

Notes

EMI = electromagnetic induction, ER = electrical resistivity, GPR = ground penetrating radar, ISFET = ion-selective field effect transistor, ISE = ion-selective electrode.

[a] Review includes remote and proximal sensors.

*Table 8.2* Soil properties influencing proximal sensors (modified from Adamchuk *et al.* 2004)

| *Category of proximal sensor* | *Agronomic soil property* | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | *Texture (sand, silt, clay content)* | *OM* | *$\theta$* | *EC or Na* | *Cp or $\rho_b$* | *Depth of topsoil or hard pan* | *pH* | *Residual $NO_3$ or total N* | *Other macro-nutrients* | *CEC* |
| Electrical and EMI | X | X | X | X | X | X | – | X | – | X |
| Optical and radiometric | X | X | X | – | – | – | X | X | – | X |
| Mechanical | – | – | – | – | X | X | – | – | – | – |
| Acoustic and pneumatic | X | – | – | – | X | X | – | – | – | – |
| Electrochemical | – | – | – | X | – | – | X | X | X | – |

Notes

EMI = electromagnetic induction, OM = soil organic matter, θ = water content, EC = electrical conductivity (salinity), Na = sodium content, Cp = compaction, $\rho_b$ = bulk density, CEC = cation exchange capacity.

To a varying extent from one field to the next, crop patterns are affected by edaphic properties. Bullock and Bullock (2000) indicated that efficient methods for measuring within-field variation accurately in soil physical and chemical properties are important for precision agriculture. No single sensor will measure all the soil properties influencing crop-yield variation; consequently, combinations of sensors have been recommended by Corwin and Lesch (2010) to add supplemental soil and plant information that can be used to better define SSMUs, resulting in a mobile multi-sensor platform. Of all of the proximal sensors, EMI and ER sensors are the most thoroughly researched and commonly used proximal sensors for the measurement of edaphic properties influencing crop yield (Corwin and Lesch, 2003, 2005a).

## Case study: delineation of SSMUs with proximal sensor-directed sampling

In a strict sense, the task of delineating SSMUs is complicated because all edaphic, anthropogenic, topographic, biological and meteorological factors influencing a crop's yield must be considered, and the SSM goals of productivity, profitability, sustainability, resource use and environmental impacts must also be taken into account. One means of simplifying the complexity of delineating SSMUs is to confine the goal to crop productivity and to define SSMUs based on one or two factors, such as edaphic and anthropogenic properties, and determine the extent of the variation in crop yield due to these factors, as done by Corwin *et al.* (2003b) and Corwin (2005).

Measurements of $EC_a$ have been used to characterize spatial variation in soil salinity, nutrients (e.g. $NO_{3-}$), water content, texture-related properties, bulk density-related properties (e.g. compaction) and leaching and organic matter-related properties (Corwin and Lesch, 2005a). As pointed out by Corwin and Lesch (2003), if crop yield correlates with $EC_a$, then $EC_a$ is measuring one or more soil properties that directly or indirectly influence crop yield. Corwin (2005) hypothesized that if $EC_a$ correlates with crop yield then it can be used to develop a crop-yield response model that can delineate SSMUs. The following case study describes the $EC_a$-directed soil-sampling methodology for delineating SSMUs based on this hypothesis.

### *Study site*

A 32.4-ha irrigated field in the Broadview Water District of the San Joaquin Valley's west side in central California (approximately 100 km west of Fresno) was used as the study site. The soil at the site is a Panoche silty clay (thermic Xerorthents), which is slightly alkaline with good surface and subsurface drainage. The subsoil is thick, friable, calcareous and easily penetrated by roots and water. Cotton was grown at the study site in 1999. In the arid southwestern USA the primary soil properties affecting cotton yield are salinity, soil texture and structure, plant-available water, trace elements (particularly B) and ion toxicity from $Na^+$ and $Cl^-$ (Tanji, 1996).

### *EC$_a$-directed soil sampling protocols*

The spatial variation of properties thought to affect cotton yield was characterized following the general EC$_a$-directed soil sampling survey protocols developed by Corwin and Lesch (2005b,c). The basic elements of a field-scale EC$_a$ survey specifically applied to precision agriculture include (1) site description and EC$_a$ survey design; (2) geo-referenced EC$_a$ data collection; (3) soil-sampling strategies based on geo-referenced EC$_a$ data; (4) soil sample collection; (5) physical and chemical analysis of pertinent soil properties; (6) statistical and spatial analysis; (7) geographic information system (GIS) database development; and (8) approaches for delineating SSMUs. The basic steps within each component are outlined in Table 8.3 and discussed in detail in Corwin and Lesch (2005b). The following describes the steps for the delineation of SSMUs at the Broadview Water District study site.

### *Site description, yield monitoring and EC$_a$ survey (steps 1 and 2)*

Site description is the first step and involves the recording of metadata to define site boundaries and the location of control points, which provide useful information for yield monitoring and EC$_a$ survey. Decisions regarding EC$_a$ measurement intensity should be based on the project objectives and scale of the project (e.g. field, landscape, basin or regional scale). For instance, a field-scale project of 30–40 ha would have measurements taken more closely together than a landscape-scale project of thousands or tens of thousands of hectares. Once this preliminary information is gathered, yield monitoring and EC$_a$ data collection can begin.

Spatial variation of cotton yield was measured at the study site in August 1999 using a four-row cotton picker equipped with a yield sensor and global positioning system (GPS). A total of 7,706 cotton yield readings was recorded (Figure 8.1a). Each yield observation represented an area of approximately 42 m$^2$. From August 1999 to April 2000 the field was fallow.

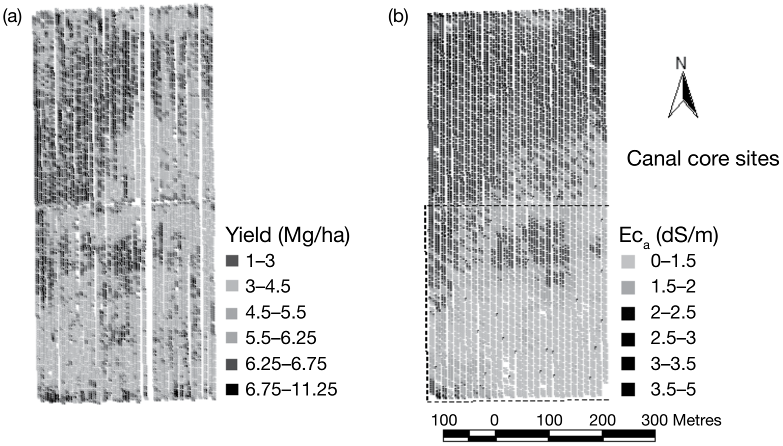

*Figure 8.1* Maps of (a) cotton yield and (b) EC$_a$ measurements including 60 soil sampling sites. Modified from Corwin *et al.* (2003b) with permission.

*Table 8.3* Outline of steps for an $EC_a$ field survey for precision agriculture applications (modified from Corwin and Lesch 2005b)

1. *Site description and $EC_a$ survey design*
    - (a) record site metadata
    - (b) define project's or survey's objective
    - (c) establish site boundaries
    - (d) select GPS coordinate system
    - (e) establish $EC_a$ measurement intensity
2. *$EC_a$ data collection with mobile GPS-based equipment*
    - (a) geo-reference site boundaries and significant physical geographic features with GPS
    - (b) measure geo-referenced ECa data at the pre-determined spatial intensity and record associated metadata
3. *Soil sampling strategies based on geo-referenced $EC_a$ data*
    - (a) statistically analyse $EC_a$ data using an appropriate statistical sampling design to establish the soil sample site locations
    - (b) establish sampling depth, sample depth increments and number of cores per site
4. *Soil core sampling at specified sites designated by the sample design*
    - (a) obtain measurements of soil temperature through the profile at selected sites
    - (b) at randomly selected locations obtain duplicate soil cores within a 1-m distance of one another to establish local-scale variation of soil properties
    - (c) record soil core observations (e.g. mottling, horizonation, textural discontinuities, etc.)
5. *Laboratory analyses of appropriate soil physical and chemical properties defined by project objectives*
6. *Statistical and spatial analyses to determine the soil properties that affect $EC_a$ and crop yield (provided $EC_a$ correlates with crop yield)*
    - (a) perform a basic statistical analysis of physical and chemical data by depth increment and by composite depths
    - (b) determine the correlation between $EC_a$ and physical and chemical soil properties by depth increment and by composite depths
    - (c) determine the correlation between crop yield and physical/chemical soil properties by depth and by composite depths to determine depth of concern (i.e. depth with consistently highest correlation, whether positive or negative, of soil properties to yield) and the soil properties that have a significant effect on crop yield (or crop quality)
    - (d) conduct an exploratory graphical analysis to determine the relationship between the significant physical and chemical properties and crop yield (or crop quality)
    - (e) formulate a spatial linear regression (SLR) model that relates soil properties (independent variables) to crop yield or crop quality (dependent variable)
    - (f) adjust this model for spatial autocorrelation, if necessary, using residual maximum likelihood (REML) or some other technique
    - (g) conduct a sensitivity analysis to establish dominant soil property influencing yield or quality
7. *GIS database development and graphic display of spatial distribution of soil properties*
8. *Select approach for delineating site-specific management unit*

In March 2000 an intensive geo-referenced $EC_a$ survey (Figure 8.1b) was conducted. Such surveys can be done with either mobile electromagnetic induction (EMI) or mobile fixed-array electrical resistivity (ER) equipment. Figure 8.2 shows mobile EMI (Figure 8.2a) and mobile fixed-array ER (Figure 8.2b) equipment developed by Rhoades and colleagues at the US Salinity Laboratory (Rhoades, 1992a,b; Carter *et al.*, 1993). The $EC_a$ survey conducted in March 2000 used the mobile fixed-array ER equipment shown in Figure 8.2b. The fixed-array ER electrodes were spaced to measure $EC_a$ to a depth of 1.5 m, which is roughly the depth of the root zone. Over 4,000 $EC_a$ measurements were recorded. Step 2 of the protocols outlined in Table 8.3 provides the basic procedure followed for the $EC_a$ survey. Details are provided in Corwin and Lesch (2005b).

*Figure 8.2* Mobile GPS-based $EC_a$ measurement equipment: (a) electromagnetic induction (EMI) rig with a close-up of the sled holding the EMI unit and (b) electrical resistivity (ER) rig with a close-up of one of the ER electrodes.

### *Sample site selection, soil sampling and soil analysis (steps 3, 4 and 5)*

Sample site selection is based on spatial variation of the geo-referenced $EC_a$ measurements. Corwin and Lesch (2010) used a response surface sampling design to minimize the number of sites needed to characterize the spatial variation in this case study. This sampling design is available in ESAP software developed at the US Salinity Laboratory (Lesch *et al.*, 2000). Sites are chosen with ESAP's response surface sampling design to (1) represent about 95 per cent of the observed range in the bivariate EMI survey data; (2) represent the average of the $EC_a$ readings for the entire field; and (3) be spatially distributed across the field to minimize any clustering. In other words, ESAP creates a three-dimensional surface of the $EC_a$ measurements and uses the variation in that surface to select sites that meet these criteria. In most instances, the number of sites selected by ESAP is not the minimum (i.e. six sampling locations per field), but is based primarily on the resources available to conduct soil sample analyses.

Following the $EC_a$ survey at the Broadview site, soil samples were collected at 60 locations based on the ESAP-95 version 2.01 software (Lesch *et al.*, 2000) analysis of the $EC_a$ survey data. These sample locations reflect the observed spatial variation in $EC_a$ while simultaneously maximizing the spatial uniformity of the sampling across the study area. Figure 8.1b shows the distribution of $EC_a$ survey data in relation to the locations of the 60 soil sampling sites. Soil core samples were taken at each site at 0.3-m increments to a depth of 1.8 m: 0–0.3, 0.3–0.6, 0.6–0.9, 0.9–1.2, 1.2–1.5 and 1.5–1.8 m. The soil samples were analysed for soil properties thought to affect cotton yield, including pH, boron (B), nitrate nitrogen ($NO_{3\_}N$), $Cl^-$, salinity ($EC_e$), leaching fraction (LF; defined as the fraction of applied water at the soil surface that drains beyond the root zone), gravimetric water content ($\theta_g$), bulk density ($\rho_b$), % clay and saturation percentage (SP). All samples were analysed following the methods outlined in Agronomy Monograph 9, Part 1 (Blake and Hartage, 1986) and Part 2 (Page *et al.*, 1982).

### *Statistical and spatial analysis (step 6)*

Statistical analyses were conducted using SAS software (SAS Institute, 1999). They consisted of three stages: (1) determination of the correlation between $EC_a$ and cotton yield with data from the 60 sites; (2) exploratory statistical analysis to identify the significant soil properties affecting cotton yield; and (3) development of a crop-yield response model by ordinary least squares regression adjusted for spatial autocorrelation with restricted maximum likelihood (REML).

### *Correlation between crop yield and $EC_a$*

The locations of $EC_a$ and cotton yield measurements did not overlap exactly; therefore, ordinary kriging was used to determine the expected cotton yield at the 60 sites. The spatial correlation structure of yield was modelled by an isotropic exponential variogram. The following fitted exponential variogram was used to describe the spatial structure at the study site:

$$v(\delta) = (0.76)^2 + (1.08)^2\,[1 - \exp(-D/109.3)], \tag{8.1}$$

where $D$ is the lag distance.

The fitted variogram model was used with the data to estimate cotton yield at the 60 sites by kriging. The correlation of $EC_a$ to yield at the 60 sites was 0.51. The moderate correlation between yield and $EC_a$ suggests that one or more soil properties that influence $EC_a$ also affect cotton yield making the $EC_a$-directed soil sampling strategy a viable approach at this site. The similarity of the spatial distributions of cotton yield (Figure 8.1a) and $EC_a$ measurements (Figure 8.1b) visually confirms the reasonably close relationship of $EC_a$ to yield.

### *Exploratory statistical analysis*

Exploratory statistical analyses were used to reduce the number of potential soil properties influencing cotton yield and to establish the general form of the cotton yield response model. The exploratory statistical analyses comprised a preliminary multiple linear regression (MLR) analysis, a correlation analysis and scatter plots of yield versus potentially significant soil properties. The preliminary MLR and correlation analyses were used to establish the significant soil properties influencing cotton yield, whereas the scatter plots were used to formulate the general form of the cotton yield response model.

Both preliminary MLR and correlation analysis showed that the 0–1.5 m depth increment resulted in the best correlations and best fit of the data to cotton yield; consequently, the 0–1.5 depth increment was considered to correspond to the active root zone. The correlations between cotton yield and soil properties in Table 8.4 show strong correlations of $\theta_g$, $EC_e$, B, % clay, $Cl^-$, LF and SP with cotton yield. The preliminary MLR analysis indicated that the following soil properties were most significantly related to cotton yield: $EC_e$, LF, pH, % clay, $\theta_g$ and $\rho_b$. $Cl^-$, B and SP were eliminated from the MLR analysis because of multicollinearity between B and $EC_e$, $Cl^-$ and LF, and SP and % clay and there were no direct cause-and-effect relationships between cotton yield and B, $Cl^-$ and SP over the ranges of measurements found (see Corwin *et al.*, 2003b, for a detailed explanation of the issue of multicollinearity).

A scatter plot of $EC_e$ and yield indicates a quadratic relationship where yield increases up to a salinity of 7.17 dS $m^{-1}$ and then decreases (Figure 8.3a). The scatter plot of LF and yield shows a negative curvilinear relationship (Figure 8.3b). Yield shows a minimal response to LF below 0.4 and falls off rapidly for LF > 0.4. Clay percentage, pH, $\theta_g$ and $\rho_b$ appear to be linearly related to yield to various degrees (Figures 8.3c,d,e and f, respectively). Even though there was clearly no correlation between yield and pH ($r = -0.01$; see Figure 8.3d), pH became significant in the presence of the other variables, which became apparent in both the preliminary MLR and in the final yield response model.

*Table 8.4* Simple correlation coefficients between $EC_a$ and soil properties and between cotton yield and soil properties. Soil properties were a composite sample of 0–1.5 m (modified from Corwin et al. 2003b)

| *Soil property*[a] | *Fixed-array* $EC_a$[b] | *Cotton yield*[c] |
|---|---|---|
| $\theta_g$ | 0.79 | 0.42 |
| $EC_e$ | 0.87 | 0.53 |
| B | 0.88 | 0.50 |
| pH | 0.33 | −0.01 |
| % clay | 0.76 | 0.36 |
| $\rho_b$ | −0.38 | −0.29 |
| $NO_3$–N | 0.22 | −0.03 |
| $Cl^-$ | 0.61 | 0.25 |
| LF | −0.50 | −0.49 |
| SP | 0.77 | 0.38 |

Notes

a Properties averaged over 0–1.5 m.

b Pearson correlation coefficients based on 60 observations.

c Pearson correlation coefficients based on 59 observations.

$\theta_g$ = gravimetric water content; $EC_e$ = electrical conductivity of the saturation extract (dS $m^{-1}$); LF = leaching fraction; SP = saturation percentage.

Based on the exploratory statistical analysis it became evident that the general form of the cotton yield response model was:

$$Y = \beta_0 + \beta_1(EC_e) + \beta_2(EC_e)^2 + \beta_3(LF)^2 + \beta_4(pH) + \beta_5(\%\ clay) + \beta_6(\theta_g) + \beta_7(\rho_b) + \varepsilon, \qquad (8.2)$$

where, based on the scatter plots of Figure 8.3, the relationships between cotton yield ($Y$) and pH, % clay, $\theta_g$ and $\rho_b$ are assumed linear; the relationship between yield and $EC_e$ is assumed to be quadratic; the relationship between yield and LF is assumed to be curvilinear; $\beta_0, \beta_1, \beta_2, \ldots, \beta_7$ are the regression model parameters; and $\varepsilon$ represents the random error component.

### Crop yield response model development

The purpose of the crop yield response model is to identify those edaphic and anthropogenic properties that have a statistically significant influence on cotton yield and to develop a quantitative relationship between cotton yield and the edaphic and anthropogenic properties. Applying ordinary least squares regression to Equation (8.2) results in the following crop yield response model:

$$Y = 20.90 + 0.38(EC_e) - 0.02(EC_e)^2 - 3.51(LF)^2 - 2.22(pH) + 9.27(\theta_g) + \varepsilon, \qquad (8.3)$$

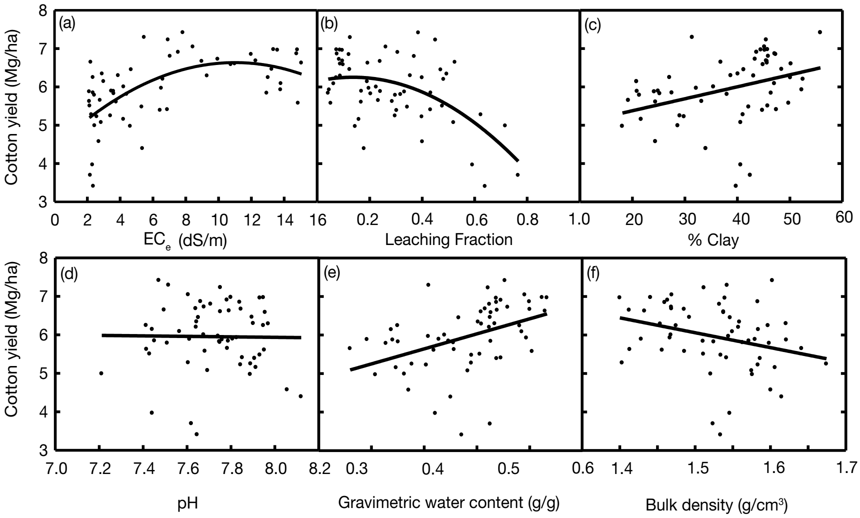

*Figure 8.3* Scatter plots of soil properties and cotton yield: (a) electrical conductivity of the saturation extract (EC$_e$, dS m$^{-1}$); (b) leaching fraction; (c) % clay; (d) pH; (e) gravimetric water content; and (f) bulk density (Mg m$^{-3}$).

Source: Corwin *et al.* (2003b) with permission.

where the non-significant *t*-test for % clay and $\rho_b$ indicated that these soil properties did not contribute to the yield predictions in a statistically meaningful manner and dropped out of the regression model, whereas all other parameters were significant near or below the 0.05 level. The $R^2$ value for Equation (8.3) is 0.61 indicating that 61 per cent of the estimated spatial yield variation is successfully described by Equation (8.3). However, the variogram of the residuals indicates that the errors are spatially correlated, which implies that Equation (8.3) must be adjusted for spatial autocorrelation.

Restricted maximum likelihood was used to adjust Equation (8.3) for spatial autocorrelation, resulting in Equation (8.4), which is the most robust and parsimonious yield response model for cotton:

$$Y = 19.28 + 0.22(EC_e) - 0.02(EC_e)^2 - 4.42(LF)^2 - 1.99(pH) + 6.93(\theta_g) + \varepsilon. \quad (8.4)$$

A comparison of measured and simulated cotton yields at the soil sampling locations showed close agreement, with a slope of 1.13, y-intercept of –0.70 and $R^2$ value of 0.57. A visual comparison of the measured (Figure 8.4b) and predicted (Figure 8.4c) cotton yield shows a spatial association between them.

Sensitivity analysis is a means of establishing how the uncertainty in the output of a model can be apportioned to different sources of uncertainty in the model input and thereby can identify the most significant model input affecting the

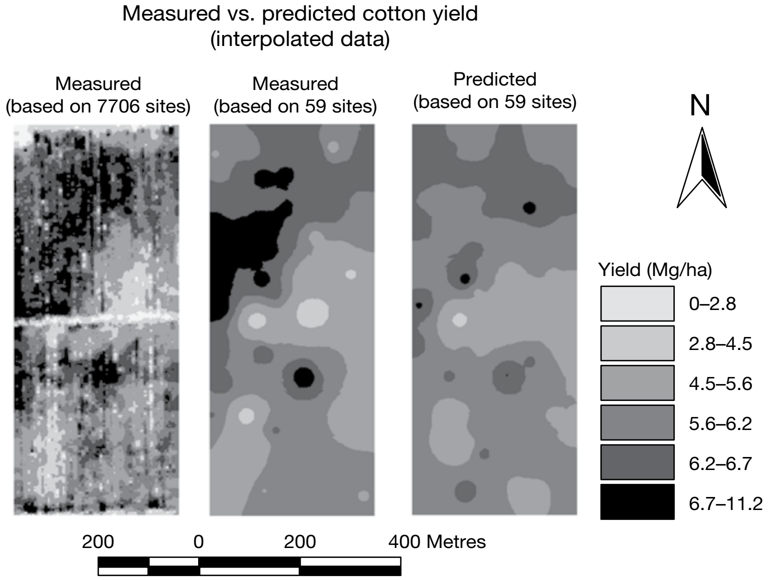

*Figure 8.4* Comparison of (a) measured cotton yield based on 7,706 yield measurements; (b) kriged data at 60 sites for measured cotton yield; and (c) kriged data at 60 sites for predicted cotton yields based on Equation (8.4).

Source: Corwin *et al.* (2003b) with permission.

output. Sensitivity analysis of Equation (8.4) reveals that LF is the single most significant factor affecting cotton yield with the degree of predicted yield sensitivity to one standard deviation change resulting in a percentage yield reduction for $EC_e$, LF, pH and $\theta_g$ of 4.6%, 9.6%, 5.8% and 5.1%, respectively.

### *GIS considerations and site-specific management units (steps 7 and 8)*

All spatial data were compiled, organized, manipulated and displayed within a geographic information system (GIS). Kriging was selected as the preferred method of interpolation because in all cases it outperformed inverse distance weighting based on comparisons using jackknifing. Figure 8.5 shows maps of the four properties that affect cotton yield significantly at the Broadview site.

With several variables, the most straightforward and practical means of defining SSMUs is to use a GIS overlay approach, which overlays criteria for each of the significant properties influencing crop yield. This approach was used to delineate the SSMUs in Figure 8.6. Based on Equation (8.4), Figures 8.3 and 8.5 and knowledge of the interaction of the significant properties influencing cotton yield in the Broadview Water District, a DSS was developed where four recommendations were established to improve cotton productivity at the study site:

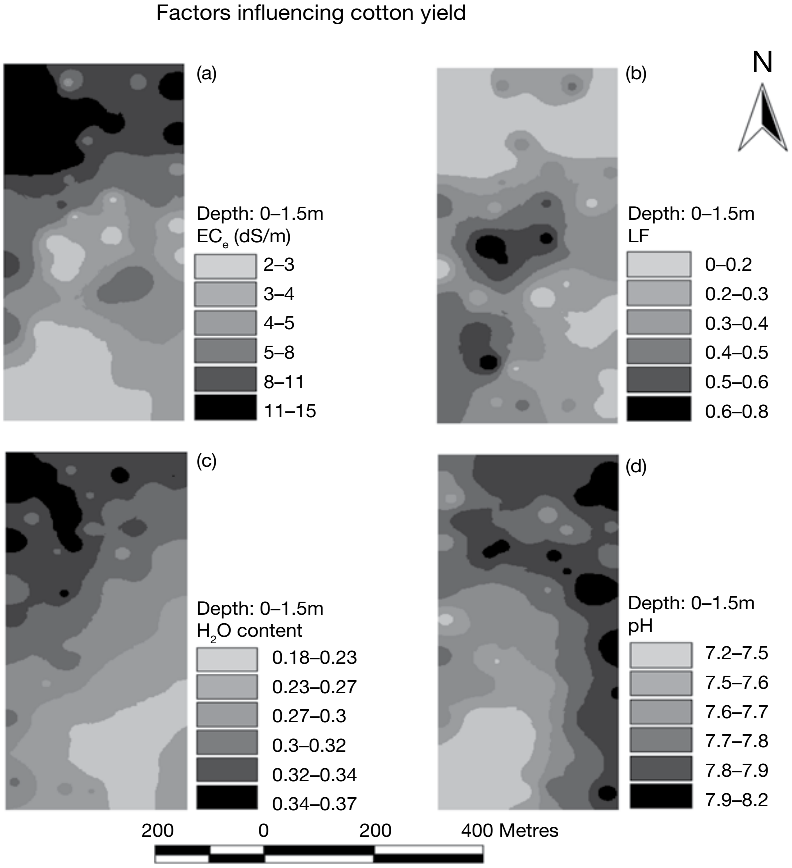

*Figure 8.5* Maps of the four most significant factors (0–1.5 m) influencing cotton yield: (a) electrical conductivity of the saturation extract ($EC_e$, dS $m^{-1}$), (b) leaching fraction (LF), (c) gravimetric water content ($\theta_g$, kg $kg^{-1}$), and (d) pH.

Source: Corwin *et al.* (2003b) with permission.

1. reduce the LF in strongly leached areas (i.e. areas where LF > 0.4);
2. reduce salinity by increased leaching in areas where the average root zone (0–1.5 m) salinity is > 7.17 dS $m^{-1}$;
3. increase the plant-available water in coarse-textured areas by more frequent irrigation; and
4. reduce the pH where pH > 7.9.

An overlay based on the four above recommendations produces the SSMUs of Figure 8.6.

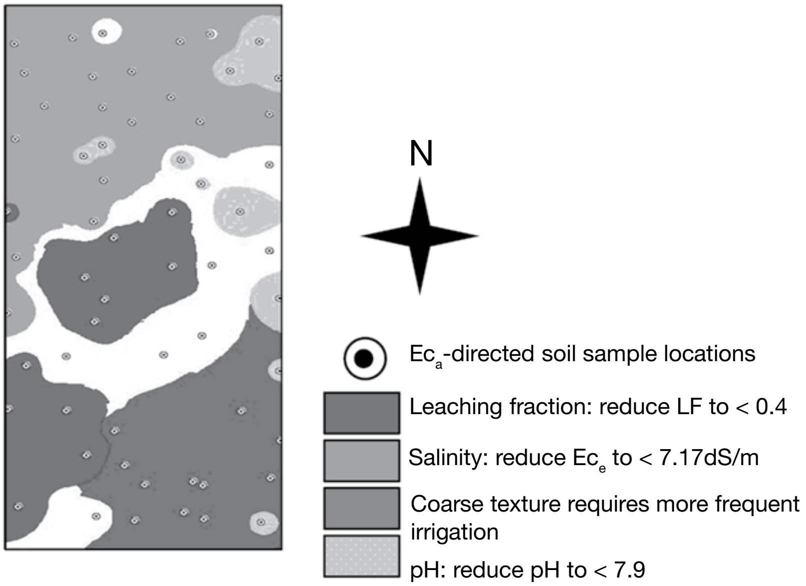

*Figure 8.6* Site-specific management units (SSMUs) for a 32.4-ha cotton field in the Broadview Water District of central California's San Joaquin Valley. Recommendations associated with the SSMUs are for leaching fraction, salinity, texture and pH.

Source: Corwin and Lesch (2005a) with permission.

Equation (8.4) identified the main properties that affect cotton yield and sensitivity analysis identified the most significant of these to be LF. The three-dimensional scatter plot of yield, LF and $NO_{3-}$ indicates that LF > 0.4 leached nutrients such as $NO_{3-}$, which resulted in a decrease in yield. The salinity level of 7.17 dS $m^{-1}$ was established by differentiating Equation (8.4) with respect to $EC_e$ and setting it equal to zero, which provided the salinity threshold (i.e. salinity level beyond which crop yield would decrease because of osmotic effects on plant water uptake). High salinity increases cotton production by producing stress in the plant and causing it to expend energy on growth of the reproductive portion of the plant (i.e. cotton bolls) at the expense of vegetative growth. However, there is a limit beyond which the osmotic effect of accumulated salinity causes the cotton plant to die. A salinity level of 7.17 dS $m^{-1}$ is the limit for the conditions in this field. The recommendation to increase the frequency of irrigation on coarse-textured areas is based on the fact that irrigation schedules were roughly every two weeks as a result of water availability and after two weeks water content was near the wilting point. Setting a limit of 7.9 for the pH is a result of the effect that high pH has on the availability of micro- and macro-nutrients to the plant.

All four recommendations can be accomplished by improving water-application scheduling and distribution and by site-specific application of soil amendments. The use of variable-rate irrigation technology at this site would enable the site-specific application of irrigation water at the times and locations needed to optimize yield.

## Beneficial impacts of SSMUS to producers and the environment

Defining SSMUs is not a trivial process, but the benefits of doing so can result in substantial rewards to the producer. Ideally, SSMUs provide producers with a means of attaining sustainable agriculture by balancing profit, depletion of finite resources, detrimental environmental impacts and crop productivity. If inputs such as water, fertilizer and pesticides are applied site-specifically, that is, *when* they are needed, *where* they are needed and in the *amounts* they are needed, then crop productivity, profit, resource utilization and environmental impacts can be optimized. The application of excessive inputs or insufficient amounts, in locations where they are not needed and/or at times when they cannot be used, does not benefit crop productivity and in fact may reduce it; it also reduces profit, wastes valuable resources and is deleterious to the environment.

For example, with conventional (uniform) applications of $NO_{3\_}N$ fertilizer there are areas of the field where excessive applications will occur. The excess N is unused by the plant, which wastes fertilizer and the producer's money, and can be readily leached through the soil or washed away in runoff water contaminating groundwater and surface water supplies, respectively. In some parts of fields insufficient inputs may be applied, which reduces productivity and profit. For example, in areas where insufficient $NO_{3\_}N$ is applied, crop yield is less than it could potentially be, which reduces the producer's profit potential. Site-specific management units identify areas within a field where $NO_{3\_}N$ fertilizer is applied in the amount and at a time and/or frequency that optimizes productivity, profit, resource utilization and limits environmental degradation.

Another example concerns irrigated agriculture. With conventional applications of irrigation water (see Chapter 10), there are areas within a field that are under- and over-irrigated. Areas of the field that are over-irrigated leach valuable nutrients from the root zone into groundwater supplies. Over-irrigation wastes water, which is a valuable resource in arid and semi-arid agricultural regions. In contrast, areas of the field that are under-irrigated cannot meet the consumptive water needs of the plant, which lowers crop yield. Furthermore, under-irrigation causes salinity to accumulate in the root zone because evapotranspiration (ET) exceeds irrigation amounts, leaving salts in the irrigation water behind, which lowers yield as a result of osmotic and specific ion toxicity effects. The site-specific application of irrigation water will minimize the leaching of salts and nutrients into the groundwater, yet adequately remove salts from the root zone to prevent a decrease in yield and provide plants with sufficient water to meet ET demands.

Growing demand for food worldwide as a result of increased calorie intake by a growing population, greater global competition for limited resources and worldwide awareness of humankind's impact on the environment make agriculture a highly competitive and crucial sector of the world's economy. To remain competitive in a global economy, producers know that they must take advantage of technology and the precision agriculture approach. Even though conventional farming practices have made incredible technological progress thanks to the Green Revolution, they are not sustainable because of the fundamental flaw that conventional farming treats heterogeneous soil in a homogeneous manner. Site-specific management provides producers with the means of taking current technology of GPS, GIS, remote sensing, variable-rate application, yield monitoring and spatial statistics to manage the spatial heterogeneity of soil to optimize productivity, profit, environmental protection and resource utilization.

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