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Editorial

Applications of apparent soil electrical conductivity in precision agriculture

Abstract

Sustainable agriculture is considered the most viable means of meeting future food needs for the world's increasing population through its goal of delicately balancing crop productivity, profitability, natural resource utilization, sustainability of the soil–plant–water environment and environmental impacts. Precision agriculture is a proposed approach for achieving sustainable agriculture. Site-specific crop management (or site-specific management, SSM) refers to the application of precision agriculture to crop production. Site-specific crop management utilizes rapidly evolving information and electronic technologies to modify the management of soils, pests and crops in a site-specific manner as conditions within a field change spatially and temporarily. Geospatial measurements of apparent soil electrical conductivity (EC_a) are the most reliable and frequently used measurements to characterize within-field variability of edaphic properties for application to SSM. The collection of papers that comprises this special issue of *Computers and Electronics in Agriculture* provides a review of the current technology and understanding of geospatial measurements of EC_a and current approaches for their application in SSM. The objective of this preface is to run a thread through the papers to show their interrelationship and to identify significant points. The spectrum of topics covered by the papers include: (i) a review of the use of EC_a measurements in agriculture, (ii) multi-dimensional EC_a modeling and inversion, (iii) theory and principles elucidating the edaphic properties that influence the EC_a measurement, (iv) EC_a survey protocols for characterizing spatial variability, (v) EC_a-directed response surface sampling design, (vi) designing and evaluating field-scale experiments using geospatial EC_a measurements, (vii) mapping of soil properties with EC_a, (viii) spatially characterizing EC_a and water content with time domain reflectometry (TDR), (ix) delineating productivity and SSM zones and (x) SSM methods for reclaiming salt-affected soils. The greatest potential for the application of geospatial measurements of EC_a in SSM is to provide reliable spatial information for directing soil sampling to identify and characterize the spatial variability of edaphic properties influencing crop

Abbreviations: CEC, cation exchange capacity; EC_a, apparent soil electrical conductivity; EM, electromagnetic induction; EM_h, electromagnetic induction measurement in the horizontal coil-mode configuration; EM_v, electromagnetic induction measurement in the vertical coil-mode configuration; ER, electrical resistivity; FKMe, fuzzy k-means; GIS, geographic information system; GPS, global positioning system; HSR, hierarchical spatial regression; RTK, real time kinematic; TDR, time domain reflectometry

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yield. This in turn can be used to delineate SSM units, which are key components of SSM. The future of SSM depends upon the continued development and integration of information and electronic technologies that can identify and characterize, both temporally and spatially, not only edaphic properties but also topographical, biological, meteorological and anthropogenic factors influencing within-field variations in crop productivity. The implementation of global positioning system (GPS)-controlled variable-rate equipment will need spatial information to effectively determine input application rates. Because of their reliability, ease of measurement and flexibility, geospatial EC_a data will undoubtedly contribute a significant portion of the spatial soils-related information needed to direct variable-rate equipment.
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Keywords: EC_a; Site-specific management units; Spatial variability; Soil quality

1. Introduction

The prospect of meeting the world's food demand for an additional three billion people over the next three to five decades is a formidable, but not insurmountable challenge. Barring unexpected technological breakthroughs, sustainable agriculture is one agronomic means of meeting this challenge. The concept of sustainable agriculture is predicated on a delicate balance of maximizing crop productivity and maintaining economic stability, while minimizing the utilization of finite natural resources and detrimental environmental impacts (Corwin et al., 1999). One of the key techniques for attaining sustainable agriculture is site-specific crop management by means of precision agriculture (Lowenberg-DeBoer and Erickson, 2000).

Site-specific crop management (or site-specific management, SSM) is a technologically driven concept that relies upon information and electronic technologies to modify the management of soils, pests and crops in a site-specific manner as conditions within a field change spatially and temporarily. The technological pieces crucial to the development of SSM first became commercially available in the 1980s and have just recently fallen into place with the maturation of the global positioning system (GPS) and geographical information systems (GIS). Many of the early stumbling blocks in the development of SSM were related to the unfulfilled promises of satellite imagery, which was perceived to be the primary sensor from which cause-and-effect variations in agricultural fields would be determined and managed. It became quickly apparent that satellite imagery was only one piece to a technologically complex puzzle that is just now being pieced together.

Crucial aspects of SSM are (i) quantification of yield variability in small areas of the field, (ii) quantification of the spatial variability of soil properties influencing yield and (iii) adjustment of inputs such as fertilizers, pesticides and seeding rates based on knowledge of soil and yield variability (Atherton et al., 1999). Bullock and Bullock (2000) point out that efficient methods for accurately measuring within-field variations in soil physico-chemical properties are needed to make SSM a reality. The geospatial measurement of apparent soil electrical conductivity (EC_a) is one of the ground-based sensing technologies that is helping to bring SSM from a concept to a reality.

The earliest applications of EC_a measurements in agriculture, primarily conducted by Rhoades and colleagues in the 1970s at the USDA-ARS Salinity Laboratory, were for the measurement of soil salinity. Due to its ease of measurement and reliability, EC_a has over the past 30 years evolved into one of the most frequently used technologies to characterize field variability for application in SSM (Corwin and Lesch, 2003). It is the goal of the special issue to provide readers with a detailed understanding of the techniques for measuring EC_a, the theory and principles of the measurement of EC_a in soil to elucidate those physico-chemical properties that influence EC_a and a comprehensive background of how the measurement of EC_a has been used in the past and how it is currently being applied for SSM. The objective of this preface is to run a thread through the papers comprising the special issue to show their interrelationship within a SSM context and to identify their most significant points.

2. Special issue organization

The special issue is organized into three sections: background information, EC_a-directed sampling and experimental design, and SSM applications. The sections consist of five, two and eight papers, respectively.

The section concerning background information consists of three papers by Corwin and Lesch, one by Friedman, and one by Pellerin and Wannamaker. The first paper by Corwin and Lesch sets the stage by covering historical development, basic principles and an overview of current applications of EC_a in agriculture. The Friedman paper concentrates on the factors influencing EC_a measurement, while the paper by Pellerin and Wannamaker provides a review of multi-dimensional electromagnetic modeling and inversion. The second and third papers by Corwin and Lesch (parts I and II) outline protocols for conducting an EC_a field survey to characterize spatial variability and demonstrate the use of the protocols to characterize the spatial variability of physico-chemical properties in a soil quality assessment of a saline-sodic soil, respectively.

The second section addresses EC_a-directed sampling and experimental design. The paper by Lesch addresses the use of the response-surface sampling design to direct soil sampling from geospatial EC_a data, while the paper by Johnson and colleagues uses geospatial EC_a data to direct and evaluate field-scale experimental design.

The final section is a compendium of papers demonstrating a variety of applications of geo-referenced EC_a data to SSM. Wraith and colleagues use time domain reflectometry to spatially characterize water content. Papers by Kitchen and colleagues and by Jaynes and colleagues deal with the delineation of productivity zones. The relationship of soil properties to EC_a and the subbasin-scale distribution of clay content based on geospatial EC_a measurements is addressed in papers by Sudduth and colleagues and by Triantafilis and Lesch, respectively. Lesch and colleagues explore the use of geospatial measurements of EC_a for salinity mapping, soil texture mapping and the location of drainage tile lines. Kaffka and colleagues analyze the relationship between EC_a, soil properties and sugar beet yield to derive SSM information and profitability implications. A methodology for site-specific soil amendment application is presented by Horney and colleagues.

2.1. Background: fundamental principles, theory and modeling, and survey protocols

As an introduction to the collection of papers in this special issue, Corwin and Lesch (2005a) provide a comprehensive review of the historical development of EC_a measurements in agriculture as well as a discussion of the basic principles, including general theory and factors influencing the EC_a measurement; different geophysical techniques for measuring EC_a; mobilized EC_a measurement equipment and applications to SSM. Friedman (2005) delves more deeply into the factors influencing EC_a measurement with a discussion of (i) how and to what extent various soil and environmental attributes affect the measurement, (ii) the physical theoretical problem, its limitations and different concepts for its analysis and (iii) the experimental and theoretical findings regarding the effects of soil and environmental attributes on the EC_a of saturated and unsaturated soils. From this discussion, Friedman (2005) provides a clear picture of the roles of the various geometrical and interfacial attributes of soil and soil solution in determining EC_a.

Pellerin and Wannamaker (2005) review the state-of-the-art in electromagnetic modeling and inversion of 1-D, 2-D and 3-D earth conductivity structures to reveal the complex relationship between actual conductivity structure and geophysical data measured near the surface. Issues that are addressed include capabilities and limitations of the various common field-measurement systems, methods to predict the geophysical response and incremental response sensitivity to earth structure, as well as techniques for iteratively estimating an earth model that maximizes resolution without sacrificing model stability. Pellerin and Wannamaker (2005) conclude that $1\frac{1}{2}$-D inversion, where resistivities and depths of local 1-D models are laterally constrained with respect to neighboring values or a large-scale average structure, may have the greatest potential for interpreting SSM datasets. They caution that lateral heterogeneity is usually more serious than researchers expect; consequently, "explicit multi-dimensional analysis is avoided only at one's peril."

Wraith et al. (2005) provide a comprehensive review of time domain reflectometry (TDR) to measure EC_a and demonstrate its application to map water content. The advantage of TDR is that it permits a direct measure of both EC_a and water content, where other methods such as electromagnetic induction (EM) or electrical resistivity (ER) do not. Although, the application of TDR to field- and landscape-scale characterization of EC_a and water content is at present not as practical for obtaining intensive spatial data as mobile EM and ER, vehicle-based TDR units are under study. Truly "on-the-fly" TDR measurements for field-scale applications may be feasible in the near future.

Protocols for conducting an EC_a survey to characterize soil spatial variability are outlined by Corwin and Lesch (2005b). The protocols consist of eight stages: (i) site description and EC_a survey design, (ii) EC_a data collection with mobile GPS-based equipment, (iii) soil sampling design, (iv) soil core sampling, (v) laboratory analysis, (vi) calibration of EC_a to EC_e, (vii) spatial statistical analysis and (viii) GIS database development and graphic display. To demonstrate their application, the EC_a survey protocols were followed for a soil quality assessment of a 32.4 ha field in California's San Joaquin Valley (Corwin and Lesch, 2005c). The results clearly demonstrate the utility of geospatial EC_a measurements for characterizing the spatial variability of certain soil properties at field scales. The protocols provide guidelines to assure the reliability, consistency and compatibility of EC_a survey measurements and their interpretation.

2.2. EC_a-directed sampling and experimental design

The second section deals with sampling and experimental design strategies based on geospatial EC_a measurements. These strategies have a far-reaching effect on the characterization of soil spatial variability and on field-scale experimental design and evaluation. Both papers in this section provide applications with relevance beyond that of SSM to include a variety of landscape-scale studies that must characterize spatial variability or account for its influence in sampling or experimental design.

The first paper by Lesch (2005) is a statistically rigorous discussion of model-based response-surface sample design strategy based on geospatial EC_a measurements to direct soil sampling. EC_a-directed soil sampling provides a means of characterizing the spatial variability of soil properties correlated to EC_a with a significant reduction in the number of sample locations as compared to grid sampling. This has widespread application to a variety of landscape-scale issues outside SSM, including soil quality assessment and modeling of non-point source pollutants in the vadose zone.

Johnson et al. (2005) detail the use of geospatial measurements of EC_a to design and evaluate non-replicated field-scale experiments. Field-scale experiments do not lend themselves to traditional experimental design concepts of replication and blocking. A comparison of the mean square errors for several soil properties and surface residue mass at a field-scale site and nearby plot-scale experiment shows that EC_a-classified within-field variance approximates plot-scale experimental error. This supports the use of within-field EC_a-classified variance as a surrogate for experimental plot error and provides a means for evaluating treatment differences in non-replicated field-scale experiments.

2.3. Applications of geospatial EC_a measurements related to SSM

The remaining papers delve into disparate applications of geospatial EC_a measurements in SSM. Each of the technical research papers in this section provides an additional piece to the SSM puzzle.

Kitchen et al. (2005) address the issue of whether productivity zones can be delineated using EC_a and elevation measurements on Missouri claypan soil fields. Productivity zones are zones of similar yield and are of use to a producer to make management decisions based upon reliable estimates of expected yield. Unsupervised fuzzy-c means clustering is used on yield data to delineate ground-truth productivity zones and on combinations of EC_a and elevation data to delineate hypothetical productivity zones. A comparison of the ground-truth and hypothetical productivity zones using an overall accuracy statistic and the Kappa coefficient reveals that there is a 60–70% agreement when combined EC_a and elevation data are used.

Productivity zones are also addressed by Jaynes et al. (2005). The delineation of productivity zones is based on a series of profiling steps in conjunction with cluster analysis to determine the relationship between yield clusters and easily measured field properties of elevation, simple terrain attribute data (e.g., slope, aspect, etc.) and EC_a. Apparent soil electrical conductivity and the terrain attributes of slope, plane curvature, aspect and depth of depression are effective in identifying soybean yield clusters. This allows easily measured field attributes to be used to approximate soybean productivity zones in similar fields where yield data may not be available.

Sudduth et al. (2005) look at the relationship of EC_a to various soil physico-chemical properties across a wide range of soil types, management practices and climatic conditions. The study is an impressive inventory of 12 fields covering six north-central states in the USA. For all fields clay content and cation exchange capacity (CEC) presented the highest correlation with EC_a. The implication of this work is that it may be feasible to develop relationships between EC_a and clay and CEC that are applicable across a wide range of soil and climatic conditions. Sudduth et al. (2005) also compare two commercial EC_a-sensing systems (i.e., Geonics EM-38 and Veris 3100[1]) on diverse soil landscape. Differences between the instruments are attributed to differences between depth-weighted response functions coupled with differences between the degree of soil profile layering from one site to the next.

Response-surface sampling design, fuzzy k-means (FKMe) classification, hierarchical spatial regression (HSR) modeling and spatial EC_a measurements are used by Triantafilis and Lesch (2005) to develop a map of the spatial distribution of clay content (averaged over the top 7 m) based on measurements taken with Geonics[1] EM34 and EM38 conductivity meters for the lower Macquarie Valley of New South Wales, Australia. The final map provides spatial information about subsurface clay variability over an area of roughly 19,000 ha and demonstrates the utility of spatial EC_a measurements in characterizing spatial variability at a scale well beyond that of a single field. Results indicate that if a grid of 250 or 125 m had been used, rather than the 0.5 km grid, a significant decrease in the predicted variance of interpolated values from the HSR model would have resulted.

The relationship between EC_a measurements, soil properties and sugar beet yields in salt-affected soil from the San Joaquin and Imperial Valleys is studied by Kaffka et al. (2005). Sugar beet yield in the San Joaquin Valley field, where drainage was impaired, is most highly correlated with saturation percentage suggesting that yield is texturally driven, while in the Imperial Valley field, where tile drainage has been effective, yield is most correlated with salinity. This work further demonstrates the utility of using EC_a measurements to establish the relationship between soil properties and crop yield for the purpose of answering resource input questions of how much, when and where, which are crucial to direct SSM. With the derived SSM information, the paper delves into the relationship between yield and profit to consider the option of taking those areas of land that are a net loss to the producer out of production.

The application of geospatial measurements of EC_a as an agricultural management tool in arid zone soils is discussed by Lesch et al. (2005). Three distinct applications are presented that demonstrate the flexibility of EC_a: salinity mapping, soil texture mapping, and tile line location.

The final paper by Horney et al. (2005) proposes a methodology based on EC_a-directed soil sampling to guide site-specific soil amendment application. The steps include: (1) generation of an EC_a map, (2) directed soil sampling for salinity, (3) determination of the estimated amendment requirement as a function of location in the field and (4) integration

[1] Mention of trademark or proprietary products does not constitute an endorsement or guarantee/warranty of the product by the U.S. Department of Agriculture and does not imply its approval to the exclusion of other products that may also be available.

of the individual amendment requirements into a practical spatial pattern for amendment application. Preliminary results for saline-sodic fields in central California do not show any statistically significant alterations in soil condition at this point. The spatial complexity of the sites and the short-term evaluation have masked any statistically perceptible evidence of reclamation.

3. Future directions

The greatest agronomic potential for EC_a in the short term is for directing soil sampling to characterize soil spatial variability. Characterization of soil spatial variability is a fundamental component of a variety of applications, such as soil quality assessment, landscape-scale solute transport in the vadose zone and SSM. Each of these applications is interrelated. Site-specific crop management depends on the quantification of the spatial variability of soil properties influencing crop productivity, which is basically an assessment of the variation of soil quality within a field where the associated management goal is crop productivity. Similarly, landscape-scale solute transport in the vadose zone is a key aspect of SSM because an intended outcome of SSM is to minimize detrimental environmental impacts to soil and water resources. These are often most easily assessed through model simulations of solute transport to determine the fate and distribution of environmental contaminants.

When geospatial measurements of EC_a are spatially correlated with geo-referenced yield data, their combined use provides an excellent tool for identifying edaphic factors that influence crop yield, which can, in turn, be used to delineate SSM units (Corwin et al., 2003; Corwin and Lesch, 2005a). The delineation of productivity zones from geospatial measurements of EC_a provides another approach to SSM (Kitchen et al., 2005; Jaynes et al., 2005). Even so, an understanding of the soil-related factors influencing yield or the identification of productivity zones does not provide the whole picture for SSM because yield is influenced by a complex interaction of topographical (elevation, aspect, etc.), meteorological (humidity, temperature, etc.), biological (e.g., pests), anthropogenic (management related) and edaphic (soil related) factors. Moreover, the precise manner in which these factors influence the dynamic process of plant growth and reproduction is not always well understood. To be able to manage within-field variation in yield it is necessary to have an understanding within a spatial context of the relationship of all dominant factors causing the variation.

Past research has shown at times that yield and EC_a do not necessarily correlate. In those instances, soil-related factors measured by EC_a were not influencing yield, but rather yield was influenced by soil factors that either were not measured by EC_a or were non-edaphic factors. For this reason, spatial knowledge of yield-influencing non-edaphic or non-EC_a-correlated factors is needed. The combined use of multiple sensors (e.g., EM, multispectral imagery, hyperspectral imagery, ground penetrating radar, Doppler radar, X-ray tomography, advanced very high resolution radiometry, aerial photography, magnetic resonance imaging, microwaves and thermal infrared) is needed to obtain the full spectrum of spatial data necessary to pinpoint the topographic, meterologic, biologic, anthropogenic and edaphic factors influencing yield. Of these, the use of hyperspectral imagery and EM measurements of EC_a combined with real-time kinematic (RTK) GPS probably have the greatest potential from a cost-benefit perspective.

Remotely sensed imagery and EM measurements of EC_a provide complementary information. Remotely sensed imagery is generally best suited for spatially characterizing dynamic properties associated directly with plant vegetative development, while EC_a measurements are best suited for spatially characterizing static soil properties such as texture, water table depth and steady-state salinity. Remotely sensed imagery is particularly well suited for obtaining spatial crop information during the maturation of a crop. Geospatial measurements of EC_a are most reliable for measuring static soil properties that may influence crop yield because of the associated soil sampling that is required for ground truth to establish what soil property or properties are influencing EC_a at a given point of measurement. Soil sampling and analysis is time and labor intensive, making the measurement of dynamic soil properties using EC_a generally untenable. Ground truth for remotely sensed imagery is also necessary, but (i) wide-coverage real-time remote images are generally easier to obtain than spatially comparable real-time EC_a data unless EC_a is measured from a airborne platform and (ii) calibrations are often faster since soil sampling for EC_a can involve several depth increments and numerous soil properties. Conventional mobilized ground-based EC_a platforms cannot begin to compete with satellite or airborne imagery from the perspective of extent of coverage of real-time data. Nonetheless, ground-based EC_a surveys at field scales have their place because they allow greater control and potentially increased spatial resolution.

There is no question that geospatial measurements of EC_a have found a niche in SSM research and practice and will likely continue to serve a significant role in the future. This special issue provides further proof that this contention is not overstated. However, additional spatial information is needed to fill gaps in the database necessary for SSM including, (i) the need for integrated spatial data of topographic, meteorologic, biologic, anthropogenic and edaphic factors influencing yield; (ii) the need for real-time data and rapid processing/analysis to enable temporal as well as spatial management decisions and (iii) the need for sensors that can measure dynamic soil properties and crop responses to those properties. The integrated use of multiple remote and ground-based sensors is the future direction that SSM will likely take to obtain the extensive spatial data that will be needed to direct variable-rate technologies. Variable-rate technologies driven by a network-centric system of multiple sensors will ultimately take SSM from a drawing board concept to a reality.

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