Agricultural Water Management 147 (2015) 144–153

Contents lists available at ScienceDirect

Agricultural Water Management

journal homepage: www.elsevier.com/locate/agwat

An approach for delineating homogeneous within-field zones using proximal sensing and multivariate geostatistics

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ARTICLE INFO

Article history:
Available online 2 September 2014

Keywords:
Soil moisture variation
Data fusion
Multicollocated factorial cokriging
LiDAR
Apparent electrical conductivity

ABSTRACT

At the landscape scale, the soil moisture distribution derives from the combination of hydrologic, pedologic, and geomorphic processes. This study uses multicollocated factorial cokriging to determine the spatial scale(s) at which soil properties and terrain attributes affect the soil moisture distribution and can be used to identify homogeneous zones in the field. Georeferenced sensing (e.g. geoelectric sensing and LiDAR) acquires real-time, non-invasive and high resolution data over large spatial extents that can be used in combination with spatial, temporal and scale-dependent information of primary interest. This study uses high resolution geoelectric and LiDAR data as auxiliary measures to supplement data obtained by the analysis of 127 soil cores taken from a 40 hectare Central Kentucky (USA) karst landscape. Shallow and deep apparent electrical conductivities (EC) were measured using a Veris 3100 in tandem with soil moisture on three separate dates with increasing soil moisture contents ranging from plant wilting point up to field capacity. Terrain features were produced from 2010 LiDAR returns collected at $\leq$1 m nominal pulse spacing. Exploratory statistics were used to identify 12 field characteristics that would be useful in determining the spatial distribution of soil moisture, including terrain features (slope and elevation), soil physical and chemical properties and geoelectric measurements (EC for each date). A linear model of coregionalization (LMC) was fitted to the matrix of direct and cross experimental variograms for the 12 characteristics. The LMC consisted of 3 basic components: nugget, spherical (short-range scale = 40 m) and exponential (long-range scale = 250 m) where each component explained 17%, 22% and 60% of the total measured variation, respectively. Results suggest that soil texture and organic matter affect the soil moisture variability. Mapping the long-range regionalized factor allows us to delineate the field into homogeneous zones. This study shows the potential for using proximal sensing and multivariate geostatistics to develop soil moisture management strategies under water stressed conditions.

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1. Introduction

There is increasing pressure on water resources worldwide. All sectors demanding water, including domestic, industry, municipal, and agriculture, are feeling the effect of current population growth on water resources. The world's population is expected to reach 9 billion by 2050 and 8 billion of these people will live in developing countries where food demand is expected to grow by at least 70 percent (FAO, 2011). As it stands in most parts of the world, rainfall alone is insufficient to meet agricultural demand. Therefore, irrigation is needed to maximize the efficient use of agricultural land. Future generations are facing the impending challenge of producing higher agricultural output with decreasing water resources. To help secure water resources and food production well into the future, it is necessary to increase the efficiency of water use in agricultural sector.

Environmental assessment approaches for strategizing irrigation input are crucial for optimizing agricultural water productivity. Farmers are well aware of the spatial variability occurring in crop production and potential benefits of site-specific (precision) farming. Factors responsible for yield variation include irrigation and fertilizer placement, field topography, genetic variation, soil hydraulic and nutrient properties, microclimatic differences, as well as pest and disease infestation (Zhang et al., 2002).

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http://dx.doi.org/10.1016/j.agwat.2014.07.013
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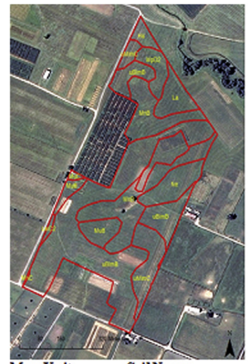
Water often plays a leading role among the factors responsible for spatial and temporal yield variability especially in dry and hot environments. Traditional irrigation techniques are designed to deliver the same quantity of water to each plant because non-uniformity in irrigation application was assumed to cause reduction in yield and water productivity. Traditional irrigation input is inefficient because it assumes that the water requirements for each plant are exactly the same and ignores the differences in crop water requirements due to spatial variability.

Precision agriculture requires matching the water inputs to crop requirements on a localized basis (Stafford, 1996). The goal of precision irrigation is to optimize the use of water resources on the basis of spatial patterns of soil properties; therefore, it becomes critical to accurately characterize soil spatial variation (Castrignanò et al., 2000). Soil surveys are commonly used to estimate crop productivity, but precision farming requires estimates at finer spatial resolutions. Therefore, adequate data analysis techniques are necessary to identify important spatial relationships between main factors controlling field variability.

One approach is to determine management zones (MZ), defined as homogeneous subfield regions with similar yield limiting factors or similar attributes affecting yield (e.g. topography, soil nutrient test levels), that can be managed separately (Khosla and Shaver, 2001; Fridgen et al., 2004). Determining MZ is difficult because of the interactions among several biotic, abiotic and climate factors that affect crop yield. Various numerical and statistical methods are used including cluster analysis (Stafford et al., 1998). Cluster analysis groups similar individuals into distinct classes in attribute space called clusters. The objective of cluster analysis is to maximize between-class variations while minimizing within-class variation. Currently, several cluster algorithms exist but no algorithm is suitable for all applications. The downside to traditional clustering techniques is to produce natural groupings of the data without any reference to geographic position. In this sense, spatial classification using cluster analysis assumes a very strong equivalence between attribute groupings and geographical map units (Beckett and Burrough, 1971; Heuvelink, 1996; Castrignanò, 2011). Factor cokriging uses a completely different analytical approach because it determines multivariate indices of spatial variation as linear combination of the attributes of neighboring observations. It can be used to subdivide an agricultural field into homogeneous management units with respect to soil physical, chemical, and hydraulic properties using the spatial covariation between georeferenced observations of different variables (Castrignanò et al., 2000). Environmental factors affecting crop response are likely to operate over different spatial scales, therefore, delineation of potential management zones is expected to be scale-dependent.

Evans et al. (1996) acknowledged that the greatest obstacle to implementing precision irrigation is the difficulty in determining accurate local applications of water and nutrients. This difficulty can be avoided by the use of real time on-the-go sensors (Adamchuk et al., 2004) which can automate the collection of soil and crop data at high resolutions. At present, several soil sensors are available which use a variety of measurement techniques (e.g. electromagnetic induction, electrical resistivity, ground penetrating radar, gamma rays, and light detection and ranging). These sensors, used in conjunction with a GPS receiver, can indirectly measure soil texture, moisture and nutrient concentrations, but their measurements are generally affected by more than one agronomic soil characteristic (Islam et al., 2011; De Benedetto et al., 2011). A sensing system that collects data on only one variable is inadequate. Most recently, researchers have focused on the development of a new approach for soil sensing, based on combining several sensing techniques to obtain a more comprehensive representation of the area under analysis (sensor data fusion). The literature on this new technique is still rather limited (Taylor et al., 2008; Nguyen et al., 2012; De Benedetto et al., 2013).



Map Unit	Soil Name	Taxonomic Description
Hu	Huntington silt loam	Fine-silty, mixed, active, mesic Fluventic Hapludolls
La	Lanton silty clay loam (dunning)	Fine-silty, mixed, superactive, thermic Cumulic Epiaquolls
MnB	McAfee silt loam 2-6% slope	Fine, mixed, active, mesic Mollic Hapludalfs
MnC	McAfee silt loam 6-12% slope	Fine, mixed, active, mesic Mollic Hapludalfs
MpC2	McAfee silty clay loam 6-12% slope	Fine, mixed, active, mesic Mollic Hapludalfs
MpD2	McAfee silty clay loam 12-20% slope	Fine, mixed, active, mesic Mollic Hapludalfs
MuB	Mercer silt loam, 2-6% slope	Fine-silty, mixed, semiactive, mesic Oxyaquic Fragiudalfs
MuC	Mercer silt loam, 6-12% slope	Fine-silty, mixed, semiactive, mesic Oxyaquic Fragiudalfs
Ne	Newark silt loam	Fine-silty, mixed, active, nonacid, mesic Fluventic Endoaquepts
uBlmB	Blue grass-Maury silt loams 2-6% slope	Fine-silty, mixed, active, mesic Typic Paleudalfs
uMlmC	Maury-Blue grass silt loams, 6-12% slope	Fine, mixed, active, mesic Typic Paleudalfs

Fig. 1. Study site and soil map.

Multicollocated cokriging is a multivariate geostatistical technique capable of integrating a variety of sensor data sets. It is possible to obtain more reliable estimates of soil properties at different spatial scales by combining proximal sensing measurements with ground-based observations using multicollocated cokriging, which can increase the efficacy of site-specific management. Hence, water and fertilizer management can be improved in terms of both timing and quantity which, in turn, will enhance agricultural water productivity and effective fertilizer use by crops.

In this paper, multiple data sets are analysed, including terrain attributes, soil physicochemical properties, soil moisture and apparent electrical conductivity (EC) measurements. The specific objectives are: (1) to study the scale-dependent correlation structure of soil variables; (2) to create simple summary indices that integrate the multi-scale data in a meaningful way; (3) to use these indices to create homogeneous management zones delineation for soil water management.

2. Materials and methods

2.1. Site description

The site investigated is at Spindletop Farm in Kentucky's Inner Bluegrass physiographic region, Fayette County, Lexington, KY (38.116030N, −84.491093W) (Fig. 1). The area is dominated by a karst landscape underlain by Orodovician phosphatic limestone, calcareous shales, and interbedded limestone shales. The site encompasses a variety of soil series illustrated in Fig. 1 (USDA-NRCS, 2013). Soil depths range from 40 to 200 cm, according to landscape position. Preliminary soil core analysis indicates argillic and fragic confining layers approximately 55–70 cm below the surface in some locations.

Site topography exhibits undulating swells (convex features) and swales (concave features). The topographic high and low are approximately 288 m and 269 m above mean sea level, respectively. A meandering creek runs N/NW of the area. A drainageway, suspected to be a relic of subsidence from the underlying karst geology, is situated diagonally (SW/NE trajectory) across the area and exhibits considerable wetness after rainfall events. Several small ($\leq$1 m^2) karst swallets reside within the drainageway. The area is exposed to a seasonal, temperate climate with a mean temperature

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