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Research Paper

Delineation of site-specific productivity zones using soil properties and topographic attributes with a fuzzy logic system

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A delineation procedure for site-specific productivity zones was developed with a fuzzy logic system using soil properties obtained from on-the-go electrical conductivity (EC) and organic matter (OM) sensors and topographic attributes. EC, OM, slope and curvature were used as input variables, and productivity was set as an output variable. The fuzzy rules were developed with grower's knowledge for typical central Kansas upland fields; areas within the field having high OM, low EC and low slope have the highest productivity potential, and areas within the field with low OM, high EC and high slope have the lowest productivity potential. The fuzzy logic system performed properly and generated productivity as designed by the fuzzy logic and inference scheme. To validate the system, an adjacent field with 5 years of wheat yield data was selected. The spatial agreement between productivity and yield showed as high as 0.57 and 0.35 for overall accuracy and kappa coefficient. The level of agreement is promising, considering there were many other yield-limiting factors such as precipitation, temperature and management effects. From comparison of the productivity map with the map generated by a fuzzy c-means clustering algorithm (FCM map), agreement between the productivity and yield exhibited generally higher in overall accuracy and Kappa coefficient than the agreement between FCM map and yield. Results of this study can benefit producers and consultants who utilise site-specific management by delineating productivity zones using EC, OM, slope and curvature from the on-the-go sensors.

1. Introduction

Site-specific management using sub-field zones is a popular way for managing soil and crop variability. For variable rate technology (VRT) application, a management zone can be considered as a sub-region of a field where a single rate of an agricultural input is applied (Doerge, 1999). Many researchers developed management zones for VRT applications in numerous ways (Fleming, Westfall, Wiens, & Brodah, 2000; Koch, Khosla, Frasier, Westfall, & Inman, 2004; Ostergaard, 1997; Zhang, Shi, Jia, Seielstad, & Helgason, 2010). Efficient and inexpensive methods, however, are necessary to delineate sub-regions for site-specific soil and crop management (Kitchen, Sudduth, Myers, Drummond, & Hong, 2005).

Various on-the-go sensors have been developed for the measurement of soil properties. On-the-go sensing provides

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increased measurement density and full field coverage at a relatively low cost. The information from soil property sensors and topographic attributes such as electrical conductivity (EC), pH, organic matter (OM), elevation, slope and curvature has been used to delineate management zones (Gessler, Chadwick, Chamran, Althouse, & Holmes, 2000; Moore, Gessler, & Peterson, 1993). Especially, electrical conductivity has been widely used in delineation of management zones because of its correlation with soil texture, which is closely related with productivity and has a strong effect on crop growth and production (Kitchen, Drummond, Lund, Sudduth, & Buchleiter, 2003; Kitchen, Sudduth, & Drummond, 1999; Kitchen et al., 2005).

Crop yield maps are considered as another approach to delineate sub-field management zones (Blackmore, 2000; Diker, Heermann, & Brodahl, 2004). Yield variations reflect within-field variations in the potential of soil productivity (Brock, Brouder, Blumhoff, & Hofmann, 2005). However, these yield maps contain numerous possible reasons for crop variability and inaccurate measurement from yield monitoring systems (Blackmore & Marshall, 1996; Lamb et al., 1995).

Fleming et al. (2000) reported that aerial photographs and topography used in conjunction with producers' previous experience were effective for creating VRT maps. Multi-temporal images using satellites have been used to study field variability in a growing season (Begue, Todoroff, & Pater, 2008). However considerable technical knowledge by end users is required to use remote sensing data (Moreenthaler, Khatib, & Kim, 2003).

For management zone delineation, clustering algorithm has been widely used to classify similar features together based on the soil properties or topographic attributes (Fraisse, Sudduth, & Kitchen, 2001). However there is no universally accepted way for delineation of management zones (Guastaferro et al., 2010; Milligan, 1996).

Unlike supervised clustering algorithms, unsupervised clustering does not need prior knowledge or information for training. Iterative self-organising data analysis technique (ISODATA) is a widely used unsupervised clustering algorithm. The ISODATA algorithm arranges the data iteratively by minimising the Euclidean distance (Tou & Gonzalez, 1974), but has a disadvantage in that variables need to possess a normal distribution and identical variances to cluster similar features by mean vectors and a covariance matrix (Fraisse et al., 2001).

Fuzzy c-means algorithm is an extensively used unsupervised clustering technique, which allows a single datum to be shared between two or more classes as controlling the degree of memberships of the datum, by a weighting exponent (Bezdek, 1981). Unlike the ISODATA algorithm, the c-means algorithm does not require variables to have a normal distribution or similar variances in the dataset (Irvin, Ventura, & Slater, 1997). Fuzzy c-means has been shown to be effective in generating management zones (Burrough, 1989; Burrough, Macmillan, & Van Deursen, 1992; Fridgen et al., 2004; McBratney & DeGruijter, 1992; Odeh, McBratney, & Chittleborough, 1992).

Farmers' knowledge can provide important information for delineating productivity variations, but is not used in such clustering methods. Producers know qualitatively which field properties tend to be more or less productive. Use of this knowledge base might delineate management zones differently based on previous management experience as explained by Fleming et al. (2000). To establish individual management zones, farmers drew vector lines on the photographs for low, medium and high productivity zones based primarily on soil colour, and their knowledge of the topography and management experience on the field. This approach can be effective to find different management zones; however, it is time-consuming and does not help on newly acquired fields, and further testing is needed to confirm the results (Fleming, Heermann, & Westfall, 2004).

Many techniques have been attempted to identify the relationship between yield data and soil properties and topographic attributes. However, it is still unclear to growers which methods to use and how to analyse results (Kitchen et al., 2003). Many soil phenomena are multi-attributed with vague conception and subjective terms (McBratney & Odeh, 1997). For example, Kitchen et al. (2003) found that "low-EC (high sand) soils with little or no slope were more productive while high-EC (high clay) soils were more productive where soils had better surface drainage" in Missouri and Kansas fields. Such vaguely defined information can be better analysed by fuzzy logic operations and inference systems (McBratney & Odeh, 1997). Papadopoulos, Kalivas, and Hatzichristos (2011) reported that a fuzzy logic system is effective for making decisions for ambiguous and uncertain environmental systems. Duru, Dokmen, Canbay, and Kurtulus (2010) also used a fuzzy logic system to develop a soil productivity profile for various types of soils in Turkey. They used pH, salinity, carbonate and OM values from laboratory analysed field soil samples as input variables and obtained soil productivity as an output.

McBratney and Odeh (1997) showed an application example of fuzzy multi-criteria decision-making (FMCDM) to describe soil mottle characteristics with a fuzzy logic system. A mottled soil surface is the indication of soil drainage conditions that is influenced by soil properties and external factors. Mottle abundance, contrast and size, with subjective, vague and conflicting connotations were selected as input variables in the system, and the strength level of mottling was obtained as an output by the fuzzy logic systems. The quantified fuzzy output was easy to perceive and process for further applications. Likewise, the FMCDM approach can be used with producers' experiential knowledge of productivity as affected by soil properties and topographic attributes to delineate productivity zones efficiently. The input of the fuzzy system is sensor data and the output of the system is the level of productivity in a field.

The objectives of this study are (1) to present a new procedure to delineate productivity zones using on-the-go EC and OM soil sensors, topographic attributes, and fuzzy logic systems along with grower's decision-making knowledge, (2) to validate it with crop yield data for an adjacent Kansas field, and (3) to compare a productivity map with a map created by fuzzy c-means algorithm.

2. Materials and methods

2.1. Research sites

Two adjacent research sites were selected for this study. The sites are located in central Kansas approximately 15 km east