Computers and Electronics in Agriculture 93 (2013) 1–9

Contents lists available at SciVerse ScienceDirect

Computers and Electronics in Agriculture

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

Rectangular shape management zone delineation using integer linear programming

Nestor M. Cid-Garcia [a], Victor Albornoz [b], Yasmin A. Rios-Solis [a,*], Rodrigo Ortega [b]

[a] Graduate Program in Systems Engineering, Universidad Autónoma de Nuevo León (UANL), Mexico
[b] Departamento de Industrias, Universidad Técnica Federico Santa María, Vitacura, Santiago, Chile

ARTICLE INFO

Article history:
Received 6 September 2012
Received in revised form 14 January 2013
Accepted 22 January 2013

Keywords:
Management zones
Zoning algorithms
Precision agriculture
Linear programming

ABSTRACT

The spatial variability of soil properties is one of the main impairments to the productivity and crop quality in agriculture. Delineating the field into site-specific management zones is usually implemented to face within-field variability. Classical zoning methods, based on soil fertility variables, have a disadvantage: the zones have oval shapes which are not practical for the variable rate technology and machinery. In this work, we present a new zoning method that optimally delineates rectangular homogeneous management zones, using relative variance to guarantee the homogeneity. This zoning method, based on soil properties, relies on an integer linear programming model that is efficiently solved to optimality. Experimental results on real and generated instances validated the method and enabled a graphical visualization of the solution.

1. Introduction

One of the main aspects of precision agriculture is to provide farming management methods to respond to within-field variability. It relies on new technologies like satellite imagery, information technology, and geospatial tools to improve the decision-making process in agricultural production. As mentioned in Ortega and Santibáñez (2007), in contrast with "traditional" uniform field management, precision agriculture permits the application in a site-specific manner of agronomic practices such as fertilization, weed and pest control, as a function of the information compiled from collected field data. The impact of precision agriculture derives from the fact that most factors determining crop yield and quality are variable in space and time. To be more efficient, management decisions must be time- and site-specific and not rigidly programmed.

Within precision agriculture, an important area is the site-specific nutrient management since there is a need of delineating management zones within fields before planting the crops to improve the overall yield. More precisely, a management zone is a sub-region of a field that is relative homogeneous with respect to soil parameters, and for which a specific rate of inputs is needed (Roudier et al., 2008). Indeed, variable rate technology uses equipment to apply inputs at a precise location to achieve site-specific application rates of inputs to reduce input and labor costs, maximize productivity, and to reduce the impact wastage on the environment. Mainly, variable rate technology in agriculture includes fertilizer, lime, seeding, and pesticides.

As mentioned by Doerge (1999), the most meaningful factors to include in a management zone strategy are those with the most direct effects on crop yield: soil moisture relationships, soil pH, soil pathogen infestation, and extremes in soil nutrient levels (see also Cambardella et al. (1994), Ortega and Flores (1999)).

Trying to delineate management zones efficiently and accurately is a mayor challenge where decision support systems are needed (McBratney et al., 2005). In this study we used data of the soil properties to propose the Integer Linear Programming Management Zone delineation method (ILPMZ for short) based on a mathematical model that could be easily inserted in any decision support system. The main advantage of the zones that the ILPMZ zoning method computes, is that they have a rectangular shape which is an important characteristic for agriculture machinery. Moreover, rectangular parcels (or portions of them) allow easier adoption of variable rate technologies based on prescription maps than irregular parcels. Additionally, this zoning method could also be applied for drip irrigation designs.

There are several approaches in the literature for properly determining site-specific management zones. Most of them are based on clustering algorithms, i.e., they are classification-based approaches.

- Approaches based on information of the soil. For example Schepers et al. (2004) and Fraisse et al. (2001) use soil and relief information; Carr et al. (1991) base their zoning on topographic

* Corresponding author. Address: Av. Universidad s/n, Cd. Universitaria, AP 111, 66450 Monterrey, Mexico. Tel.: +52 8114920363.
E-mail address: yasmin@yalma.fime.uanl.mx (Y.A. Rios-Solis).

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http://dx.doi.org/10.1016/j.compag.2013.01.009

maps; while methods of Mulla (1991), Mortensen et al. (2003), and Bhatti et al. (1991) need soil sampling.

- Approaches based on yield maps, combining data from several seasons. We can cite Blackmore (2000), Diker et al. (2004) and Pedroso et al. (2010). Doerge (1999) pointed out that crop yield patterns from yield maps may not be stable enough across seasons to accurately define management zones without supplemental information.
- Integration of the two previous approaches as in Whelan et al. (2003), Franzen and Nanna (2003), Hornung et al. (2003, 2006). In Roudier et al. (2008) they use a watershed segmentation algorithm where the user can introduce morphologies of the desired zones.

The combination of the different layers of information can be performed by a cluster procedure using K-means or Fuzzy K-means methods (Ortega et al., 2002; Li et al., 2005; Jiang et al., 2011), or principal component analysis with a cluster method (Ortega and Flores, 1999). The Fuzzy K-means algorithm is widely used and the choice of the data layers processed by the clustering is an issue (Jaynes et al., 2005). A major drawback is the resulting fragmentation of the zones (Simbahan and Dobermann, 2006; Frogbrook and Oliver, 2007; Li et al., 2005). Moreover, this zones are oval shaped and disjoint due to the clustering methods.

Fig. 1 schemes the real word problematic we solve in this work: Some farmers become aware that precision agriculture leads to important saving (e.g., in fertilizers) by delineating management zones. For this, they invest in soil samples of their fields that are then analyzed in a laboratory (dots in the maps are the places where the soil samples where taken). The results of the properties of the soil samples can be visualized as thematic maps like the one in the left upper part of Fig. 1 (Organic Matter (OM) is used as soil property and MapInfo as visualization software). By using a clustering method (e.g., the one in MapInfo software) with the organic matter as soil chemical property we obtain the upper right map of the same figure. Each color of this map represents a management zone (green, orange, light blue, and dark blue). We can notice that the resulting zones are disjoint and are irregular shaped which difficulty the use of machinery and therefore the application of resources and inputs. Farmers then think about tracing a grid and delineate their own zones based on the clustering zones or on the thematic map which results in any of the solutions presented in the bottom of Fig. 1. The drawback of this approach is that there is an exponential number of different possible management zone delineations. In order to find the best delineation, farmers must try all of them (e.g., compute the costs of fertilizers) and this would literally take years to be completed. With the ILPMZ method we offer the farmer the best management zones delineation in minutes such that they are rectangular and the most homogeneous possible within each zone.

To the best of our knowledge, this is the first approach that directly offers rectangular shape zones which is an important characteristic for variable rate technologies since it facilitates the work and operation of machinery. Indeed, broadcast seeders (used for spreading lime or fertilizer), manure spreader or sprayers are usually towed behind a tractor. If a management zone is rectangular then it is easier for the farmer to indicate its limits to the tractor driver. Therefore, agricultural inputs are spread exactly in the management zone that requires them.

The ILPMZ method delineates the most homogeneous rectangular management zones from a field with respect to the properties of the soil. It consists of three main stages:

(a) *Instance generation*. In this stage, data from grid soil sampling of a given field is processed: for each soil sample we have its coordinates, and a set of soil properties (pH, organic matter, phosphorus, nitrogen, etc.). Then, a thematic map of the field is created with respect to the wished soil property (or properties) and all the quarters (or potential zones) are computed together with their variances.

(b) *Mathematical model*. With the input of stage a), we propose an Integer Linear Programming (ILP) that is then solved with a branch and bound algorithm. The aim of the ILP is to find a set of the most homogeneous quarters that minimizes the sum of their variance and that covers the whole field.
A main contribution is the insertion of the relative variance into the model to guarantee the homogeneity of the managements zones.

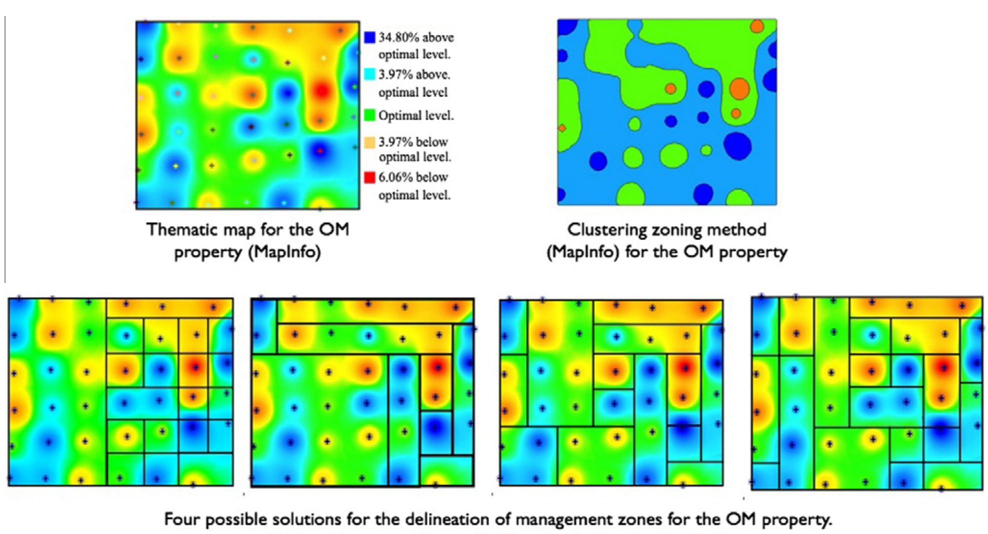

Fig. 1. Left upper map: thematic map for the organic matter property (OM) obtained with MapInfo. Right upper map: Clustering zoning method from MapInfo for the OM property. Each color of this map represents a management zone (green, orange, light blue, and dark blue). Bottom maps: four (out of millions) different solutions of management zones obtained by making a grid based on the smallest size of a zone. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)