Computers and Electronics in Agriculture 107 (2014) 20–28

Contents lists available at ScienceDirect

Computers and Electronics in Agriculture

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

A crop planning and real-time irrigation method based on site-specific management zones and linear programming

Nestor M. Cid-Garcia [a,*], Angel G. Bravo-Lozano [b], Yasmin A. Rios-Solis [a]

[a] Graduate Program in Systems Engineering, Universidad Autónoma de Nuevo León (UANL), Mexico
[b] Unidad Académica de Agronomía, Universidad Autónoma de Zacatecas (UAZ), Mexico

ARTICLE INFO

Article history:
Received 3 July 2013
Received in revised form 28 May 2014
Accepted 8 June 2014

Keywords:
Soil properties
Crop planning
Real-time irrigation
Linear programming

ABSTRACT

We present two mathematical models that consider the physical and chemical site-specific management zones within the parcels. Indeed, the spatial variability of these properties directly impacts the agricultural production planning. The first model is for the crop planning problem. At the beginning of the production cycle, it assesses the chemical and physical management zones to determine the optimal crop pattern for maximizing the farmer's expected profit. The second model is a real-time irrigation method that takes the solution of the crop planning problem as input. Then, at each irrigation period, it considers the physical management zones and the humidity level of each parcel to determine in real-time the optimal amount of water for each crop irrigation. This is especially important in regions where droughts are frequent. We empirically show that our methodologies are efficient on instances based on real data.

1. Introduction

At the beginning of the production cycle, farmers must decide which crops they are going to plant in each one of their parcels. It is one of the most complex decisions since it is impacted by the spatial variability of the physical and chemical soil properties within each parcel. Soil variability directly affects crop pattern choice because it has great impact on water balance, nutrient dynamics, and response to the application of inputs (seeds and fertilizers). For example, if a parcel is rich in nitrogen and phosphorus then planting maize or tomatoes could lead to higher yields without using much fertilizer. However, if half of the parcel is poor in nitrogen, then the farmers may decide to fertilize only half of the parcel instead of fertilizing it entirely.

Moreover, the crop planning decisions must also consider several factors as the expected prices of crops yielded, the expected amount of available water for the production cycle, the cost of irrigating a parcel (some parcels may be far away and their irrigation may consume more electricity), the phenological stages of the crops, the number of hectares in each parcel, the expected amount of resources, and so on.

In this paper, we propose a methodology to help the farmers to consider all these attributes to determine the optimal crop pattern to maximize the farmer's profit; we call this problem as the Crop Planning Problem (CPP). For this, the farmers must first delineate chemical and physical management zones within their parcels. A management zone is a sub-region of a parcel, which expresses a relatively homogeneous combination of yield limiting factors, for which a single rate of a specific crop input is appropriate (Ortega and Santibáñez, 2007; Al-Karadsheh et al., 2002; McBratney et al., 2005). Managing fields as zones helps to reduce input costs (Moore and Wolcott, 2000; Doerge, 1999). To facilitate the use of agricultural machinery, these management zones should have a rectangular shape. Farmers can then use the ILPMZ method proposed by Cid-Garcia et al. (2013) that efficiently creates rectangular shape homogeneous management zones.

The main chemical soil properties that a farmer might consider are pH, organic matter rate, phosphorus, and nitrogen.[1] The main physical soil properties are: field capacity or permanent wilting point, which is based on the texture, structure, and porosity of the field, and influences the movement and retention of water; air and solutes in the soil, which impact plant growth and organism activity. All these properties may be altered by management practices that are usually expensive. It is therefore imperative to consider which zones need theses practices. Fig. 1 shows an example of the chemical and physical management zones (at the right hand side of the figure) of three parcels (at the left hand side of the figure) determined by the

* Corresponding author. Tel.: +52 (81) 83294000x5945.
E-mail addresses: nxtr.cd@gmail.com (N.M. Cid-Garcia), a_bravo2002_2@hotmail.com (A.G. Bravo-Lozano), yasmin.riossls@uanl.edu.mx (Y.A. Rios-Solis).

[1] The properties suitable for a specific crop in Mexico are available in SAGARPA or in INIFAP. In other countries they can be found in FAO.

http://dx.doi.org/10.1016/j.compag.2014.06.002
0168-1699/

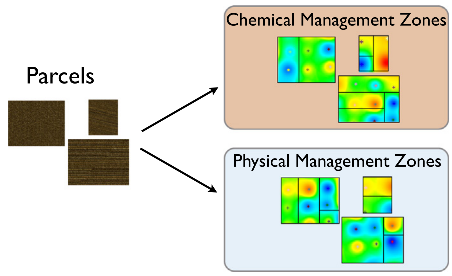

Fig. 1. Chemical and physical management zones of three parcels.

ILPMZ method. Notice that the number and size of the physical and chemical zones are different for each parcel. In Chile, Ortega et al. (2002) have demonstrated that the use of management zones based on soil properties, produces a positive impact on vineyards and traditional crops.

An important contribution of this study is to solve the CPP that considers the chemical and physical management zones of the parcels to decide the optimal crop pattern. Then, at the beginning of each irrigation period, in order to decide the optimal water irrigation level for each parcel, farmers need to consider a number of factors: the physical management zones of their parcels; the crops planted in each one; the phenological stages of the crops; the real-time humidity of the soil determined by sensors, and the available water. These decisions are crucial, especially in arid and semiarid regions, since farmers seek to maximize total profit. We call this the *Real-Time Irrigation Problem* (RTIP), and it is also a key contribution of this paper.

Control strategies that locally modify the irrigation volumes must be adaptive in order to use scarce resources more effectively (McCarthy et al., 2008; Smith et al., 2009). The linear programming model we present for RTIP considers the yield response to water shortages, the climate conditions, the evapotranspiration of the crops in a specific geographical region, and the phenological stage of the crops. In this manner, with RTIP we use only the necessary amount of water or, if there is a water shortage, RTIP determines which parcels to fully irrigate, which ones must be under deficit irrigation, and which ones will be lost, to optimize the allocation of water resources.

This article is structured as follows. In the rest of this section we make a brief literature review. Then in Section 2.1, the CPP is presented together with its mathematical model. The output of this problem serves as input for the model of RTIP (Section 2.2). In Section 3, we show that our new approaches are efficient with instances based on real data. Section 4 concludes this work. A summary of the mathematical notation can be found in Appendices A and B.

1.1. Related literature

Sarker et al. (1997) propose a linear programming model to solve the CPP that considers land type, alternative crops, crop patterns, input requirement, investment, and output. Later, Sarker and Ray (2009) formulate a CPP as a multiobjective optimization model. A major result of their work is that their algorithm delivers superior solutions to the nonlinear version.

Mainuddin et al. (1997) propose a crop planning model for an existing groundwater irrigation. Adeyemo and Otieno (2010) present an evolutionary algorithm to solve the multiobjective crop planning model: minimize the total irrigation water, to maximize both the total net income from farming and the total agricultural output. Itoh et al. (2003) consider crop planning under uncertainty.

In Casadesús et al. (2012), Xu et al. (2011), Hedley and Yule (2009), Hassanli et al. (2009) the authors propose heuristics for scheduling irrigation plans according to weather conditions, crop development, and other factors. A work that is closely related to ours is Alminana et al. (2010), where they present models and algorithms to determine water irrigation scheduling by taking into account the irrigation network topology, water volume, technical conditions, and logistical operations. McCarthy et al. (2013) review the existing literature of advanced control process in irrigation.

Few works deal with both crop and irrigation problems as we do in this research. Ortega Álvarez et al. (2004) propose a nonlinear model solved by genetic algorithms to identify production plans, and water irrigation management strategies. They estimate crop yield, production and gross margin as a function of the irrigation depth. Sahoo et al. (2006) propose fuzzy multiobjective linear programming models for land-water-crop system planning. Reddy and Kumar (2008) present a multiobjective approach for the optimal crop pattern and operation policies for a multi-crop irrigation reservoir system.

As we see from the literature review, there are several studies concerning CPP or RTIP which use real-time information in their methodology from a great diversify of technological devices, as humidity sensors, as we do in this work. However, few approaches use this real-time information to feed mathematical models and execute them in real-time too. This is an important characteristic because we can give to farmer a response in real-time from the current conditions (weather, water, seeds, etc.). Moreover, for both mathematical models, CPP and RTIP, we propose exact solutions (optimal solutions) in an efficient period of time, instead of approximations. Many of the previous methods consider management zones but, to the best of our knowledge, this is the first approach which uses rectangular and homogeneous physical and chemical management zones with mathematical programming.

2. Materials and methods

In this section we present our methodologies for the crop planning problem (Section 2.1) and and real-time irrigation problem (Section 2.2).

We use the term field for the whole land that can be irrigated by a water well or a dam. This field is made up of different parcels. In each parcel j a single crop i is going to be planted. Each parcel j is subdivided into z management zones (Fig. 2). All the management zones z of a parcel j must be planted with the same crop i. This is by farmer requirement, as they prefer not to have more than one crop in the same parcel. We could easily modify the model to plant a different crop in each management zone if necessary.

2.1. Crop Planning Problem, CPP

The CPP problem decides which crops i to plant in different parcels j considering the chemical and physical management zones of these parcels. The farmer's objective is to maximize the total expected profit given a limited expected water availability for the production cycle.

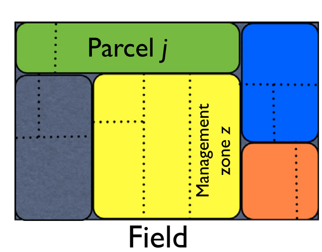

Fig. 2. Terms used in this article: field, parcel, and management zone.