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A computational approach for crop production of organic vegetables

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ABSTRACT

This paper deals with a vegetable production-planning problem in which a farmer has to simultaneously determine the crop rotations and harvest schedules for a number of vegetables in his farmlands. The crop rotation decisions include the determination of crop sequence, cropping times, and cropping size in each farmland. The harvest decisions include the collection times and harvesting size for each planted crop. By taking into account the growing season and technical-ecological constraints, this paper formulates a mixed integer linear programming model to develop vegetable production decisions for organic farmers. Due to the complexity of the model, we proposed a two-phase heuristic approach to solve the model. We applied the proposed model to analyze an organic farm in Taiwan. Computational results show that the proposed heuristic is superior to CPLEX in terms of solution quality and computational times for large scale problems. In addition, some sensitivity analyses were also conducted to evaluate the impact of parameters in the model.

1. Introduction

The demand for organic foods, such as organic vegetables, fruits, and coffees, increase in the recent years. The global organic food market grew from US$ 57.5 billion in 2010 to US$ 104.7 billion in 2015 with an estimated compound annual growth rate (CAGR) of 12.9%. It is expected to continue to steadily grow. According to the report of Global Organic Food Market Forecast & Opportunities by TechSci Research, the global organic food market is estimated to grow with a compound annual growth rate of 16% through 2020.

Organic fruits and vegetables are the biggest-selling organic category of organic foods. In this paper, we focus on the organic vegetables. Usually farmers of organic vegetables must determine what kinds of vegetables to plant and how to design the growing schedule in line with guidelines such as natural law and the technical-ecological rules.

The natural law requires that vegetables be planted in their designated growing season. With regard to the technical-ecological rules, two experiments are usually considered. The first is to avoid the cropping style of continuous growing two crops of the same botanic family on the same piece of land because this may have a dramatic impact on plant root zones and result in decreasing soil fertility or crops that are susceptible to diseases, plagues, or weeds (Haneveld and Stegeman, 2005). Thus, farmers usually adopt this rule to provide essential chemical elements in quantities and proportions for the growth of specified plants. The second is to use fallow lands to build soil structure and reduce pest damage (Santos et al., 2010), or to use green manures to cover bare patches of soil between crops or during intervals between one crop and the next to maintain and improve soil fertility.

To satisfy the above growing requirements and considerations, many farmers have used crop rotation techniques to make their cropping plans. Crop rotation is the process of growing different types of crops on a piece of farmland over each growing season. The purpose of the approach is to determine the cropping sequences and their cropping sizes in a piece of farmland (Santos et al., 2011). The decisions for crop rotations have a critical impact on crop yields over the long term.

Over the past decade, many works have been proposed to deal with the crop rotation problems. Most of them focused on determining the right crop rotation for a specific field to maximize the crop yield. Plant (1997) pointed out that expert systems and numerical simulation models are two useful methods to develop crop decisions.

(i) Expert systems use different methods such as artificial intelligences to convert data from complex eco-systems into available information to develop crop strategies and tactics (Chakraborty and Chakrabarti, 2008). Artificial intelligence focuses on how to combine computer equipment, software, and specialized information to imitate human experts in making decisions. In this area, Dogliotti et al. (2003, 2006) proposed a computational program,

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ROTAT, to produce crop rotations based on agronomic criteria. This approach firstly generates a crop-rotation pool composed of all possible permutations of crops, and then selects feasible crop rotations from the produced pool. (ii) Numerical simulation models adopt the simulated mechanical systems to mimic the natural behavior to reproduce the processes of a system in an analog or digital fashion to generate decisions. This approach numerically solves the equation without any turbulence model and applies a sort of numerical time-stepping procedures to generate natural behavior over time (e.g., Stockle et al., 2003).

In addition to the above approaches, many mathematical models have also been proposed to study variant crop-production planning problems (e.g., Sarker et al., 1997; Sarker and Quaddus, 2002; Haneveld and Stegeman, 2005; Detlefsen and Jensen, 2007; Santos et al., 2010; Moghaddam and DePuy, 2011). These models use mathematical concepts and language to describe the behavior of a crop system.

Sarker et al. (1997) formulated a linear programming model to deal with a crop planning problem for optimizing contributions through the determination of allocation of different land types, land availability and suitability, capital, and import bounds. Sarker and Quaddus (2002) proposed a goal programming approach to solve a multi-objective crop-planning problem. Haneveld and Stegeman (2005) developed a mathematical model to investigate an agricultural production-planning problem with the consideration of crop succession requirements. They assumed that the crop succession requirements are dependent on the types of crops grown and developed an algorithm to determine the crop sequences. Their paper aims to determine the crop sequences and their cropping sizes on a piece of land. However, their model does not consider the cropping location on the piece of land and the harvest schedule. Detlefsen and Jensen (2007) developed network flow models to study a crop rotation problem for a given selection of crops on a piece of land. Santos et al. (2010) considered a sustainable vegetable crop supply problem to maximize production volume or revenues by determining the best division of various heterogeneous pieces of land under known demands. They proposed a mathematical model to investigate this problem with known demand, ecologically based production constraints, and multi-planting areas. Their paper determined the division of the available heterogeneous arable areas in plots and crop rotation schedule for each plot to maximize revenues. However, the production lengths and the productivity of each harvesting for all crops are predetermined.

Due to the computational complexity, most complex mathematical models are usually incapable of producing system parameters or exact solutions for completed systems within reasonable computational time. Therefore, many authors have devoted to finding compromised solutions within reasonable time instead of using incredible computational time to find optimum solutions. These approaches, including the already-mentioned numerical simulation (e.g., Stockle et al., 2003), approximation techniques (e.g., Haneveld and Stegeman, 2005), and the evolutionary computation approaches (e.g., Sarker and Ray, 2009), have been used to solve the variant problems. The evolutionary computation approach belongs to the artificial intelligence approach and well-known algorithms include ant colony, particle swarm optimization, genetic algorithms, and so forth. Sarker and Ray (2009) formulated a multi-objective mathematical model to deal with a crop-planning problem. They proposed a genetic algorithm based on a multi-objective constrained algorithm to solve the problem.

A vegetable's harvestable periods may consist of several days or several weeks. Usually, the harvest schedule for ripe vegetables' collection times and size is based on market demands. Since demands are usually dispersed evenly over time, farmers will harvest their ripe corps several times to match supply with demands as fit as possible. Thus, some researchers have focused on harvesting-scheduling problems. Higgins et al. (1998) presented a mathematical model to discuss the harvesting-scheduling problem. The purpose of their model is to maximize the sugar yield and net revenue through the determination of harvest date and crop age. Muchow et al. (1998) investigated the problem of optimal harvesting time for sugar production. The decisions include (i) when to harvest different crop classes over the long harvesting period and (ii) the time at which crops are harvested (or planted) in the previous year. Moghaddam and DePuy (2011) investigated a farm-management problem for the horse breeding industry. The problem was formulated as a chance constrained mathematical model in which inventory is allowed. The paper aims to maximize the total profit by determining hay growing, buying, and selling decisions. They adopted the linear approximation technique and LINGO software to develop decisions. Foulds and Wilson (2005) developed an integer programming model to describe a harvesting-scheduling problem for renewable resources, and proposed heuristics to solve the model. Piewthongngam et al. (2009) developed a numerical simulated model to determine the best combination of cane cultivar, planting dates, and harvest dates. Although the above-mentioned literature deals with harvest scheduling problems, it does not consider crop rotation constraints.

Most rotation works assumed that the length of crops' harvest periods is fixed and does not consider vegetables' inventories. That is, a crop is harvested when its growing periods reach the given maturity time length. Santos et al. (2010), the most recent and relevant study to our work, assume that each crop is harvested only one time and did not consider inventory. However, in practice, harvested vegetables can be stored fresh to satisfy future demands, and vegetables can be harvested during the interval of maturity date to their maximum permissible growing date beyond which crops are over-maturity and have lost their values. Thus, farmers do not necessarily harvest once, and they can stock harvested vegetables to satisfy future demands. Some farmers will attempt to satisfy demand by inventory. Thus, crop rotation production scheduling problems with variable harvesting times and size are worth researching.

To our knowledge, no work simultaneously deals with the crop rotation and crop harvesting-scheduling problems. However, these two problems usually occur simultaneously. To fill the gap in the research, in this paper we assume that: (1) For multi-harvests, ripe vegetables can be collected during the entire harvestable interval. The harvest interval of a crop is from its maturity date to its maximum permissible growing period. (2) Vegetable inventories and their holding costs are considered. The operation process of this study includes planting, growing, harvesting, inventory, and supply. The purpose of this paper is to maximize the total expected revenues over a given planning interval through the determinations of (i) what kind of crops to plant, (ii) how many and when to crop, (iii) which farmlands to crop, and (iv) when to harvest under the condition that growing requirements are satisfied.

2. Model assumptions and formulation

The manager of C organic farm has decided to plant vegetables in its L cultivation-houses over T planning periods. The area of cultivation-house-ℓ is A^{ℓ} m^2. The planting combination is selected from a candidate vegetable pool which consists of K types of vegetables. The K types of vegetables are divided into U botanical families. Vegetable type-k belongs to botanical family of q^k.

While planting vegetables, the farmer should obey some planting guidelines: (1) Season requirement: each type of vegetable should be planted during its suitable planting season. Let $w_t^k = 1$