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Modelling optimal crop sequences using network flows

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Abstract

In recent years there has been an increased focus on sustainable farming systems. This has led to an increase in the use of farm models built to assess the environmental impact from farming. In whole-farm models including crop production it is important to consider the rotation of crops, since this has a major impact on the consequences of the crop production.

The problem considered in this paper is that of finding an optimal crop rotation for a given selection of crops on a given piece of land. It is shown that techniques from network modelling can be used to model this problem, which has the advantage that special algorithms for solving network problems can be developed and applied to solve the crop rotation problem. This can save computation time and make it tractable to implement crop rotation in whole-farm models.

Keywords: Crop rotation; Network flows; Linear programming; Crop sequence; Farm model

1. Introduction

With the increased focus on sustainable landscapes – and farms are an important part of the landscape – there is an increased focus on building models of farming systems at different scales to assess the agricultural, economical and environmental impacts of farming. These whole-farm models are able to predict the impacts of different scenarios. The scenarios could be different management options or different policies, markets, resources or other regulations. Some of these models include the crop production only, some models include the livestock production only and some include both.

Keating and McCown (2001) recognize two key components of farming systems, namely the biophysical 'Production System' of crops, pastures, animals, soil and climate, together with certain physical inputs and outputs, and the 'Management System', made up of people, values, goals, knowledge, resources, monitoring opportunities, and decision-making. They see major challenges and opportunities in combining 'hard', scientific approaches to the analysis of biophysical systems and 'soft' approaches to intervention in social management systems.

The rotation of crops has a major impact on environment and productivity (yield, diseases, soil characteristics, etc.). Therefore, whole-farm models that include crop production must somehow include crop rotations as an important component. ROTAT is a method developed by Dogliotti et al. (2003) to systematically generate all possible crop rotations from a given number of crops satisfying a given set of rules (for example crop rotation criteria). However, no effort is made to optimize the rotations. ROTAT has subsequently been used to assess different consequences of farming such as sustainable farming, soil fertility and farm income in case studies in South Uruguay (Dogliotti et al., 2004, 2005, 2006).

The decision support system for agrotechnology transfer (DSSAT) (Jones et al., 2003) is a result of the recommendations from the International Consortium for Agricultural

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Systems Applications (ICASA). One of the main purposes of ICASA is to advance the development and application of compatible and complementary models, data and other systems analysis tools. DSSAT is a collection of independent programs related to crop simulation models, which are capable of interacting with each other. Programs contained in DSSAT allow users to simulate crop management options over a number of years to assess the risks associated with each option. Even though the crop rotation is an important part of crop management, the user has to provide this as input to the simulation.

CropSyst (Stöckle et al., 2003) is a suite of linked programs providing users with a set of tools to analyze the productivity and the environmental impact of crop rotations and cropping systems management at various temporal and spatial scales. The crop rotations in this system are given as input by the users.

Cabrera et al. (2005) describes the computer implementation of the Dynamic North Florida Dairy farm model (DyNoFlo Dairy), which is a decision support system that integrates nutrient budgeting, crop, and optimization models created to assess nitrogen (N) leaching from North Florida dairy farm systems and the economic impacts resulting from reducing it under different climatic conditions. The crop models from DSSAT (Jones et al., 2003) are used and the crop rotations are user-defined. In Cabrera et al. (2006) the DyNoFlo Dairy model is used to demonstrate how the North Florida dairy farms can reduce N leaching by selecting management practices using climate forecasts.

Crop rotations have traditionally been optimized by means of linear programming (LP). Klein Haneveld and Stegeman (2005) developed an LP-model for solving the crop rotation problem based on sequences of crops that can follow each other. They start with a piece of land on which a number of different crops have to be grown. First they allocate the different crops to different crop sequences and then use a max-flow network problem to determine a cropping plan for one year. There has not yet been any report of it being used in a whole-farm model.

In Denmark agricultural losses of nitrate, ammonia and nitrous oxide are scrutinized by national and international environmental authorities. This scrutiny is accompanied by increasing restrictions on farm management. This has led to the development of a decision support tool (FarmN-Tool) that allows environmental regulators and farmers/farm advisors to assess the losses of nitrogen from a farm. The internet-based tool has a demo in English, which can be accessed via: http://www.Farm-N.dk/FarmNTool.

The FarmNTool requires the user to input information on the mixture of crops grown in each rotation. The rotations are typically linked to the soil types, rather than to actual fields. The required information is crops and area of each crop. Then the crop sequences are calculated and this succession is used to determine expected yields, nitrogen needs, etc. The model used to calculate these crop sequences is the topic of this paper.

The model is closely related to the model described by Klein Haneveld and Stegeman (2005). However, we use principles from network flow modelling, where Klein Haneveld and Stegeman (2005) use standard LP. A network flow model is a linear programming model with a special structure. We show how network flow modelling can be used to model the crop rotation problem, hence algorithms for solving networks can be used to solve the crop rotation problem.

The next section defines the crop rotation problem to be modelled. Section 3 gives a short introduction to network modelling. A simple model taking a single precrop year into account is described in Section 4, whereas a model taking two precrop years into account is described in Section 5. The advantages and disadvantages of the given formulations are finally discussed.

2. Definition of the crop rotation problem

Normally, a crop-producing farmer has the same fields over several years, and a range of crops is grown on the fields every season. The succession of crops in a given field influences the production through parameters like yield, nitrogen requirements, disease pressure, etc. Therefore, the farmer must try to find the optimal succession of crops for the fields of the farm.

Various objectives could be selected for optimization criterion, but the objective must be one that depends on the crop sequences and is comparable. For example the yield depends on crop sequences, but it must be expressed as the monetary value, rather than the actual harvested amounts, in order to be comparable between crops.

Note, that the model cannot predict the optimal crop sequence with respect to minimal environmental impact, since this depends on the entire farm management. However, if the model is embedded into a whole-farm model, the environmental consequences of the crop rotation can be predicted. In most cases, farmers would request the economically optimal crop sequence, so the aim is to build a model that can simulate the crop rotation problem from the farmer's perspective and determine the crop sequence with the highest expected gross margin.

Ideally, the model can take a number of previous seasons into account to predict the optimal distribution of areas of crops for this and for a number of future production years.

2.1. Example

To illustrate the model we will use a simple example in this and the following sections. The farm in the example has 35 ha. of fields, and every year 20 ha. of spring barley (B), 5 ha. of winter rape (R) and 10 ha. of clover grass (C) should be grown.

We choose gross margin as the objective to be optimized, so we need to calculate this. Some parts of the calculation, like the cost of ploughing and harvesting, can be