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The impacts of crop yield and price volatility on producers' cropping patterns: A dynamic optimal crop rotation model

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ABSTRACT

A dynamic optimization model is developed to show how crop yield and price volatility could impact acreage response under crop rotation considerations. By maximizing net present value of expected current and future farm profits, a modified Bellman equation helps optimize planting decisions. Our model is capable of simulating crop rotations with different lengths and structures. The corn–soybean rotation was simulated using the model to determine break-even prices for alternative planting decisions. Furthermore, we assume that the extent to which crop yields are penalized when skipping a rotation scheme is not fixed. Then we investigated the relationship between yield penalty levels and break-even corn price percentage changes. By considering both 1-year and 2-year carry-over effects which represent how previous crops affect current crop yield, our results indicate that producers are more likely to choose a crop rotation scheme when yield penalties are higher.

1. Introduction

Around the world, crop rotation – planting alternative crops on the same agricultural land in consecutive seasons – has been a popular agricultural practice for centuries. Rotations are employed to reduce disease risk and pest damage while maintaining soil quality for crop growth. A prevalent example of a rotation's agronomic benefits is the corn–soybean rotation, where soybeans provide a key nutrient (nitrogen) for corn growth (Hennessy, 2006). In terms of net returns, crop rotations generally reduce input costs and improve soil productivity, thereby increasing expected returns compared to continuous cropping (Hurd, 1994; Berzsenyi et al., 2000; Meyer-Aurich et al., 2006). They also tend to reduce yield risks (Helmers et al., 1986; Nel and Loubser, 2004; Meyer-Aurich et al., 2006).

Rotational effects also impact management decisions. Mullen et al. (2005) conducted a survey focused on the determinants of Georgia producers' crop choice and crop acreage allocation decisions. Results of the survey indicated that 80% of producers ranked rotational considerations as one of the two most important factors influencing their crop choices, and 66% of producers ranked rotational considerations as one of the two most important factors influencing their acreage allocation decisions. Although crop rotation has many benefits, it can also serve as a production constraint, hindering the ability of producers to adjust acreage in response to changing market conditions. Switching from crop rotation to continuous cropping to take advantage of favorable market conditions such as sudden price surges could be financially beneficial in the short run while leading to long-run yield losses and associated lower net returns (Livingston et al., 2012). In recent years, as corn prices have risen sharply, many producers have allocated more acreage to corn. However, this immediate short-run return could be offset in the long run by yield losses associated with increased pest pressure and less favorable agronomic conditions due to continuous cropping.

Crop rotations have been intensively studied by both agronomists and economists. The agronomic literature demonstrates that crop rotations improve or maintain crop yield while reducing input demands for fertilizers and pesticides. Johnson et al. (1998) estimated that Georgia cotton and peanut yields from a cotton–peanut rotation were 26% and 10% greater, respectively, than those from continuous cropping. In Michigan, Roberts and Swinton (1995) demonstrated that corn rotated with soybeans improved corn yields by 16% compared to continuous cropping. Vyn (2006) reported that a corn–soybean rotation in Indiana enhanced corn yields by about 6%. Discrepancies among agronomic results indicate that crop rotation effects may largely interact with various external factors such as soil type and fertilizer input, increasing the difficulty of developing economic models of crop rotation.

The above agronomic model generally shows the effects of crop rotation on crop yield, which is not capable of aiding the farmers' acreage decision under the volatility of both crop yield and crop

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price. As noted in Wu et al. (2004), there is a need for dynamic economic models of acreage decisions. Incorporating the yield effects of crop rotations is an important component of such a model. However, crop rotation effects are surprisingly omitted in many acreage response studies. Some researchers incorporate a lagged acreage variable in an econometric acreage response model, attempting to represent crop rotation effects (Bewley et al., 1987; Weersink et al., 2010). This lagged variable represents the magnitude of rotational constraints to acreage response, while the interactive effects of crop rotation on producers' behavior are not captured.

A number of economic approaches have been applied to model crop rotation. Using linear programming, a pioneer study of crop rotation was conducted by El-Nazer and McCarl (1986). The major contribution of their study is allowing the model to determine the optimal rotation, while most researchers use predetermined rotations. Multi-year crop rotations were modeled using an annual equilibrium linear programming approach. Hennessy (2006) developed an economic model of crop rotation to analyze and separate the interconnected crop rotation effects of yield-enhancement and input-saving carry-over effects. Both 1-year and multi-year carry-over effects were considered. Their model focuses on choosing among alternative rotations. Detlefsen and Jensen (2007) modeled crop rotation with network modeling. Their model provides a visual representation of the crop rotation problem.

As the first in the literature to model sequential planting decisions considering crop rotations in a dynamic optimization framework, Livingston et al. (2012) used the Bellman equation, which helps solve dynamic sequential problem, to examine crop choices with price uncertainty over an infinite time horizon. Compared to previous literature, dynamic programming simulates sequential optimal decision making process and fits well into crop rotation.

Various crop rotation models developed in recent years have broadly expanded our knowledge. We attempt to contribute to the literature by providing a dynamic optimization crop rotation model with minimum agronomic restrictions, such as soil type, yield response, and rotation structures. In addition, instead of focusing on fixed yield penalty taking from specific region, we conduct a sensitivity analysis towards how the variations in yield penalty related to crop rotation could affect producers' planting decisions. As showed in the above agronomic literature, yield penalties do have large spatial variations, thus producers' optimal decisions should vary by region as well. Livingston et al. (2012)'s yield penalty is fixed in a specific region. Although both incorporating the Bellman equation, we assume that all of the crops in a rotation are planted in the same season, while Livingston et al. (2012) assume sequential crops planted on the same land for continuous seasons. In reality, most producers actually plant all crops in crop rotation simultaneously in the same season with the purpose of reducing production risk and balancing labor load. Due to this different crop rotation planting assumption, we model dynamic optimization process differently from Livingston et al. (2012). For example, we have different state variable, control variable, and state transition function for the Bellman equation. Our model may be less computationally demanding since we only have nine states for 1-year carry-over effect, while Livingston et al. (2012)'s model contains about 2,000 evaluation points in the state space for 1-year carry-over effect. In this paper, we aim to answer the following main research question: What is the optimal cropping plan over multiple growing seasons considering the economics of crop rotation in a dynamic framework? To address this question we construct a dynamic model of economic decision making that explicitly accounts for the impact of crop rotation on economic returns over multiple growing seasons.

In the remainder of the paper, we first present the modified Bellman equation for crop rotation. Then we demonstrate our key model feature – a causal flow for the state transition, which helps incorporate crop rotation in a dynamic programing. Finally, we take the corn–soybean rotation as an example for our crop rotation model and discuss the simulation results.

2. Methodology

2.1. Crop rotation model

We start with a crop rotation system with two crops, A and B, planted on two equal-sized tracts of land. A producer plans to maximize the sum of current and expected future farm returns for certain years considering the effect of crop rotation. At the beginning of each season, the producer considers the previous season's crop, and decides which crop to plant on the same tract of land for the current season. It is assumed that the current crop yields are determined by both the previous and current seasons' planting decisions. If the producer decides to follow the rotation practice by switching the crops between the two tracts of land, crop yields for both A and B would be maintained at the rotational level, assuming fixed inputs of fertilizer and pesticide. If the producer decides to plant only crop A on both tracts of land, its yield in one of the tracts would decrease due to continuous cropping. Therefore, crop rotation is a Finite-Horizon Markov Decision Process, which can be simulated using the Bellman equation (Bellman, 1957). In the Bellman equation, sequential decisions are optimized to balance an immediate reward against expected future rewards (Miranda and Fackler, 2002). The basic elements for the Bellman equation, such as the state variable, control variable, and state transition function are demonstrated as follows.

The producer makes planting decisions by considering the crops planted during the previous season; therefore, we take crop choice and crop yields at time $t-1$ as the state variable for time t.

$$y_{t-1} \in \{y, ym\} \tag{1}$$

where y denotes the yield of crop y due to crop rotation, and ym denotes the reduced yield of crop y due to continuous cropping. Price is exogenous in this study and is used to convert yield into profit in the Bellman equation.

Since we assume that the producer plants alternative rotational crops simultaneously during the same growing season and switches crops between two tracts of land for the next season, the size of state space is determined by the rotation length. We use A–B to represent a rotation scheme with crop A planted for 1 year and crop B planted for another year. A rotation with crops A and B could also have a different structure such as A–A–B, which means crop A is planted for two consecutive years and B is planted for the third year. For a rotation with two crops A and B, denoted by A–B, the number of elements in the state space is nine, which includes all possible combinations of yield and reduced yield for crops A and B as follows:

$$y_{t-1} \in (\mathrm{A|B, A|BM, AM|B, A|A, A|AM, AM|AM, B|B, B|BM, BM|BM}) \tag{2}$$

where A|B represents that crop A is planted on one tract of land with full yield, and B is planted on the other tract of land with full yield. AM or BM represents the crop with reduced yield due to continuous cropping. AM|BM is not involved in the state space. AM|BM indicates that both A and B are harvested with reduced yield due to continuous cropping, so the crops planted during the previous season must be crops A and B. While both crop A and crop B are planted for two consecutive seasons, we assume the producer will switch the tracts of land for A and B and obtain crop rotation yield A|B, as opposed to the continuous cropping yield AM|BM. Therefore, AM|BM is not included as a possible yield scenario.

The control variable for the Bellman equation, the producer's crop choice, is: