Corn or Soybean? Dynamic Farmland Allocation Under Uncertainty

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In agricultural industries, one of the key determinants of the farmer's profitability is the allocation of the farmland among multiple crops for planting. Consider, for example, the farmers in the U.S. Each year, the majority of these farmers decide how to allocate their land between corn and soybean, which are the major crops in the U.S. with overlapping growing seasons (The Economist, 2011). The main objective of this paper is to develop a theoretical basis for understanding the tradeoffs facing a farmer in the farmland allocation decision in a multi-period framework.

There are unique characteristics of farmers that present challenges for the allocation decision. First, there exists *revenue uncertainty in each growing period*. The revenue is determined by the farm-yield and the sales price of the crop, and thus, the revenue uncertainty is driven by the uncertainty in these factors. In particular, the farm-yield (the harvest volume) can be lower than the planted volume due to unfavorable weather conditions, and infestation of pests and diseases during the growing period (Kazaz and Webster 2011). Moreover, because agricultural products are commodities, there exist regional exchange (spot) markets; and the sales price of the harvested crop depends on the prevailing spot price on the day (Goel and Tanrısever 2013). The spot price shows considerable variability; and it is uncertain at the time of the allocation decision. Second, there exists *crop-rotation benefit across growing periods*. In particular, planting a different crop in consecutive periods in a given farmland is more profitable than planting the same crop. As highlighted by Hennessy (2006), the crop-rotation benefit is driven by two main factors: Rotating crops can *i*) improve the farm-yield by adding nutrients to the soil and breaking the pest cycles; *ii*) decrease the farming cost by reducing the need for fertilizers (due to improved soil organic matter) and pesticides (due to lower pest populations).

The farmland allocation problem has received considerable attention in the operations management and agricultural economics literatures. However, the majority of papers focus on either single-period models (for example, Huh and Lall 2013), where crop-rotation benefit is not relevant; or multi-period deterministic models, where revenue uncertainty is absent. The few papers, which consider both revenue uncertainty and crop-rotation benefits, focus on simple heuristic allocation policies (Livingston et al. 2014). In summary, there is no work

in the literature that characterizes the optimal dynamic allocation policy, and studies the key determinants of profitability under the optimal policy. In this paper, we attempt to fill this void.

To this end, we consider a multi-period optimization problem in which a farmer periodically decides how to allocate his fixed farmland (which is normalized to a single acre without loss of generality) between two crops to maximize his expected profit over a finite planning horizon. In each period, the farmer makes the allocation decision with respect to revenue (per acre) uncertainty, incurring a unit farming cost for each crop and considering the crop-rotation benefits. To capture these benefits, we assume that, for each crop, the unit farming cost is lower and the revenue is stochastically larger when this crop is planted in a rotated land (where the other crop was planted in the previous period). We assume that crop revenues follow a a single-factor bi-variate mean-reverting process with Markovian property, i.e. the current revenue realizations are sufficient to characterize the distribution of future revenues.

With this model, we answer the following research questions: 1) What is the optimal dynamic allocation policy? 2) How does the revenue uncertainty impact the farmer's profitability? 3) What is the benefit of using the optimal policy relative to heuristic allocation policies which are implemented in practice? In answering the last two questions, we calibrate our model to represent a typical farmer in Iowa that plants corn and soybean. We conduct numerical experiments using realistic instances. These instances are chosen based on the publicly available data from United States Department of Agriculture, complemented by the data obtained from the existing literature. We summarize our main findings below:

The Optimal Dynamic Allocation Policy. We show that the optimal allocation in each period can take three different forms, fully allocate the farmland to corn or soybean; and rotate each crop, i.e. plant each crop only in the rotated farmland from the previous period. We characterize a recursive operator for each crop in each period that determines the optimal allocation. We show that the expected profit over the entire planning horizon can be uniquely characterized by the same operator.

Impact of Revenue Uncertainty. We conduct sensitivity analysis, both analytically and numerically, to investigate the impact of corn and soybean revenue volatility and revenue correlation on the farmer's profitability. We find that the farmer benefits from a lower correlation. Interestingly, the farmer benefits from a higher revenue volatility only when this volatility is sufficiently high. Otherwise, a lower revenue volatility increases the profitability.

Comparison with Heuristic Allocation Policies. Paralleling the extant literature, we consider three simple heuristic allocation policies which can be characterized in closed form, and thus, can be implemented in practice: monoculture policy (where the same crop is planted over the entire planning horizon), always-rotate policy (where each crop is planted in the rotated land from the previous period) and myopic policy (where the allocation decision in each period is made by ignoring its impact on the subsequent periods). Because these heuristic policies ignore the revenue variability in choosing the allocation; we propose a new heuristic policy, one-period lookahead policy (where the allocation decision in each period is made by considering the expected profit from the current and the subsequent periods). We characterize the allocation decision under the proposed policy in closed form. We find that the proposed policy outperforms the other heuristic policies; and it does not lead to a significant profit loss in comparison with the optimal policy. We also find that the profit loss is very significant when the monoculture policy is implemented. The key implication of this result is that crop-rotation benefit crucially impacts the profitability, and thus, the farmer should not ignore the crop-rotation possibility in choosing the allocation policy.

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