Dynamic Crop Production Responses to Realizations of Weather and Production with Application in Jordan

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1 Introduction

Uncertainty of output quantities and prices shape farming decisions across the globe. This axiom holds true in the semi-arid areas of Jordan too, where farmers must adapt throughout the calendar year to manage production risk due to the magnitude and timing of the onset of rains. In order to understand and model the response farming practiced by the Jordanian farmers where decisions are made in a dynamic setting with explicit time dimensions in a risky environment, a dynamic and stochastic modelling approach is required.

Agricultural production decisions are shaped by the stochastic interactions of crop growth, weather, and financial outcomes. Moreover, crop production decision are made with due consideration of the livestock production decisions where both decisions are often made simultaneously - making a systems modelling approach a must. Incorporation of the biological responses with economic (dis)incentives, while intuitive, presents many challenges in modelling. Optimizing agents respond to current biological developments, with only past distributional knowledge (as opposed to perfect foresight into the future). The choice of the type and timing of production decisions is important for determining outcomes both in the short-run (e.g. yields, revenues, etc.), as well as in the long-run (e.g. soil moisture and soil organic matter). Producers choose which crops to plant, how much and when to apply inputs, whether to graze their animals on the crop/residue and when and what to harvest. These choices influence the profitability of production each year within a stochastic environment, and when incorporated in a single year model can easily be optimized. However, current agricultural production decisions also influence future profitability through their effect on soil properties, such as soil moisture or organic carbon, which are important for both the long term sustainability of the household, and avoiding environmental degradation. Optimization models analyzing intra-seasonal stochastic production and dynamic inter-seasonal resource management present a modeling challenge due to the often encountered curse of dimensionality, where model size increases exponentially with the number of time periods and stochastic events.

In his paper, dynamic programming (DP) with a portfolio model is used to overcome the issues discussed above and develop an agricultural systems (AS) model. The AS model developed here values the production trade-offs of short- and long-run outcomes, within a stochastic choice model. This methodology allows for the dynamic testing and valuation of various production technologies, including conservation agriculture and crop varieties.

2 Materials and Methods

The approach is illustrated with a model of representative agricultural households in Jordan, specifically within the Karak Governorate. Data for generating model parameters is obtained from crop and weather simulators and household survey. As the data required for a dynamic bio-economic model are intensive and mostly unavailable through historical records, the Agricultural Production Systems Simulator (APSIM) is calibrated at the local level to generate crop yields given various weather and managerial choices (Keating et al. 2003). To generate a rich distribution of outcomes conditional on production choices and weather conditions, the LARS-WG 5.5 (Semenov 2010) was used, the outputs of which served as inputs for APSIM.

Data were collected at the household level by the International Center for Agricultural Development in the Dry Areas (ICARDA) to define farm household typologies for testing the sensitivity of results and households to differences in various endowments. Households are small-holder farms in the semi-arid region of Central-Western Jordan, typically relegated to barley and wheat production with no access to irrigation for field crops.

A two-part dynamic stochastic model was created to efficiently model conditional production decisions and short- and long-run economic incentives for the farming system. While a single Discrete Stochastic Program (DSP) might be preferred, dependence of transition probabilities for soil attributes (i.e. moisture and organic carbon) across years on managerial choices is not consistent with the DSP approach. For this reason, the soil attribute management problem is addressed in part one of the modeling system using a stochastic DP model over a ten year horizon using discrete choices of crop/conditional management strategies to derive the long-run value of soil attributes. The DP models an optimizing agent maximizing time-discounted returns within and across years given stochastic outcomes and conditional production choices. The resulting dynamic solution, provides estimates of the long-term marginal value of carry-over soil attributes.

Part two of the dynamic stochastic model is based on a single year portfolio model. The choices available can be thought of as investment assets which are defined by set crop/conditional management strategies that fully specify the management practices for the crop given weather outcomes. The distribution of returns to these assets is evaluated for each of the simulated weather years and reflects both the value of crop products (grain and fodder) and a term for valuing the ending stocks of soil attributes derived from the DP model of part one. Choices in the portfolio model are continuous allowing for diversification across crops and input levels to allow for computationally less restrictive risk management strategies. While the portfolio model may seem static at first blush, the incorporation of management choices that depend upon weather outcomes (e.g. timing of planting conditioned on rainfall, weather conditions that trigger fertilizer applications, etc.) make this model effectively dynamic as well as stochastic. The incorporation of a valuation of soil attributes as it affects future production possibilities can be intuitively analogous to the co-state variable in a dynamic Hamiltonian or the expected future returns in a Bellman's equation, where decisions are optimized for a single period given the conditionally optimized future periods.

Combining these two dynamic models builds upon the strengths of each to produce an efficient and tractable system for modeling inter- and intra-seasonal choices. The stochastic process in both models is driven by the combined weather and crop simulation models to provide a large enough sample to generate rich distributions of the returns to crops and conditional managerial strategies. The stochastic portfolio model can be considered similar to a DSP, however, the model defines choices through thresholds and ranges in each time period, as opposed to simplified discrete states. The threshold and range modelling approach does not require state specific assumptive transitional functions, thus maintaining the observed biological process of crop production. The combined DP and portfolio approach capture the short- and long-run benefits and costs of agricultural production in such a way that allows the imposition of constraints in a household modeling framework, such as limits on labor and liquidity, consumption requirements, etc. These household specific features with the combined approach allow for testable hypotheses to the effects of household endowments on choices and outcomes.

3 Results - Discussion

The results of the model will show both the importance of dynamic intra-seasonal management responses, as well as the impact of long-run soil valuations on production choices. Optimizing agents balance the trade-offs of short-run income and financial constraints/preferences with the incentives to manage soil quality which has implications on flow of benefits in the future. With the incorporation of the valuation of soil parameters, optimizing agents, both risk-neutral and risk-averse, will adopt crop rotations and diversified land allocations. The impact of taking a myopic view that does not place a value on soil attributes is also assessed.

The model is also used to assess the long-term benefits of innovations such as residue retention and zero-tillage for increasing the sustainability of the farming system by better management of soil attributes, showing the importance of incorporating the financial incentives with the biological trade-offs. As planting strategies influence current year outcomes, they also directly influence the distributions of the end-of-year soil attributes, which determines future production potential. The results illustrate the dynamic trade-off, through the valuation and incorporation of soil attributes, of zero- versus conventional tillage.

4 Conclusions

We develop a two-part dynamic stochastic model that integrates the stochastic biological process with the financial and economic incentives of crop production. Land use and input decisions are based on short- and long-term trade-offs of current and future returns which includes the impact of weather-related risks. By analyzing the long-run horizon through a dynamic programming model that ignores short-run constraints on household resources, we derive a dynamic valuation of soil attributes. This valuation is then used in a short-term dynamic, stochastic model of the household that focuses on issues of crop mix and the diversification of conditional management strategies for the purpose of measuring the sustainability of the household and their resource management strategies. This hybrid approach results in a tractable model which can be used to optimize production behavior over both the short- and long-run.

References

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