Modeling Producer Responses with Dynamic Programming: A Case for Adaptive Crop Rotations

David Boussios[1]*, Paul V. Preckel[2], Yigezu A. Yigezu[3], Prakash Dixit[3], Samia Akroush[4], Hatem Cheikh M'hamed[5], Mohamed Annabi[5], Aden Aw-Hassan[3], Yahya Shakatreh[4], Omar Hadi[4], Ayed Al-Abdallat[4], Jamal Abu El Enein[6], and Jamal Ayad[6]

Selected Paper prepared for presentation at the 2017 Agricultural & Applied Economics Association Annual Meeting, Chicago, Illinois, July 30-August 1

[1]U.S. Department of Agriculture, Economic Research Service, Washington, DC, USA
[2]Department of Agricultural Economics, Purdue University, West Lafayette, IN. USA
[3]International Center for Agricultural Research in the Dry Areas (ICARDA), Amman, Jordan
[4]National Center for Agricultural Research and Extension (NCARE), Amman, Jordan
[5]National Institute for Agronomic Research in Tunisia (INRAT), Tunis, Tunisia
[6]The University of Jordan, Amman, Jordan.

* Corresponding Author. Physical Address: 355 E Street SW, Washington, DC, 20224. Email Address: david.boussios@ers.usda.gov. This analysis was largely undertaken while the corresponding author was working at Purdue University, and any opinion or conclusions of the author does not reflect those of the Economic Research Service or the U.S. Department of Agriculture. This work was partially supported by the International Center for Agricultural Research in the Dry Areas grant number 14044242.

Introduction

Past research has found that producers' conditional responses are important adaptations to weather outcomes and other stochastic events. Failing to recognize these responses may overstate the consequences of risks confronting producers and understate their ability to respond to adverse circumstances. The need for assessing long time horizons to develop sustainable systems suggests dynamic programming (DP) as a means for determining management plans. However, most DP analyses based on annual time steps take producer choices as fixed strategies within the year (Burt and Allison, 1963; Farquharson et al., 2008; El-Nazer and McCarl, 1986; Jones, Cacho, and Sinden, 2006; Livingston, Roberts, and Zhang, 2014). Here, we suggest an alternative approach in which the within year strategies incorporate conditional responses that depend on the outcomes of random variables during the year.

Method

Using an approach to DP that allows for conditional production decisions that depend on realizations of random variables during the year, the method optimizes cropping decisions over an infinite time horizon that includes reactions to stochastic weather during the year. Data for the model was generated using a weather simulator (LARS-WG 5.5) and a crop and soil simulation model (APSIM).

Within year responses to weather are incorporated in the annual choices of crop management strategy through the use of conditional choices. That is, instead of each choice of next crop in the rotation conditional on the state variable reflects multiple potential crop and management choices depending on the realization of weather as it unfolds over the year. Choices in the model include: [TABLE 1]. Random variables within the year are defined similarly to those in discrete stochastic programming; however, threshold levels are used to define stochastic triggers for choices. Threshold levels categorize weather years into similar groups within which management choices are the same.

Random variables are realized prior to two periods: planting and 60 days following planting. Planting occurs when 100 mm of rainfall has accumulated from the beginning of the crop year, and the choice of crop and cultural practices is affected by when this threshold has been reached. Four periods define the grouping of weather years with respect to the timing of planting: before Dec. 26th, Dec. 27th to Jan 16th, Jan 17th to Feb 1st, and insufficient rainfall by Feb 1st. Following planting, another threshold is used to indicate whether rainfall persisted past planting; the threshold level is 100 mm 60 days after planting.

The following defines one instance of a conditional choice of crop and farming practice that is a potential choice for the year conditional on the DP state variable:
1. If the date when 100 mm of rainfall has accumulated is before December 26, plant barley with 100 kg, DAP applied at planting.
2. If the date when 100 mm of rainfall has accumulated is between December 26 and January 17, then plant wheat with 100 kg DAP applied at planting.
3. If the date when 100 mm of rainfall has accumulated is between January 18 and February 1, plant wheat with 50 kg. DAP applied at planting.
4. If 100 mm rainfall has not accumulated by February 1, fallow.
5. Sixty days after planting (whenever that occurred), side dress fertilizer at the following rates: if planting was prior to December 26 apply urea at a rate of 40 kg/ha; if planting occurred between Dec 26th and January 17 apply 40 kg/ha of urea; if planting was between Jan 18 and February 1 do not apply urea; and if planting was on February 1 do not apply urea.

The discrete state, discrete time DP is solved using the CompEcon Toolbox provided by Miranda and Fackler (2002). Adaptions to the solver allowed for larger numbers of choices. The principle of the approach lies in holding select choices constant for given states and iterating potential choices over the fixed set to find the best possible combinations of conditional choices.

Results

Three model scenarios illustrate the benefits of using conditional crop/management strategies and attempt to shed light on why farmers do not in general follow Extension recommendations regarding fertilizer application rates. The first scenario only allows fixed choices of crop/fertilization/harvest strategy at the beginning of the year conditional on the soil state (soil moisture, organic matter, and available nitrates). The second scenario allows for conditional choices of

crop/fertilization/harvest strategy depending on the realization of random weather variables within the crop year. The first and second scenarios only consider fertilizer application rates that are observed in the field in Jordan – 50 kg/ha, or half of the Extension recommended level. The third scenario expands the set of potential fertilizer application rates to include the higher rate of 100 kg/ha.

Results of Typical Static Within-Year DP Crop Model [FIGURE 1]
Results with Conditional Stochastic Responses [FIGURE 2]
Results with Conditional Stochastic Responses and Agronomic Recommended Fertilizer Levels [FIGURE 3]
Comparison of Results Across Models: Rotational Differences [FIGURE 4]
Comparison of Results Across Models: Steady-state Solutions [TABLE 2]

Conclusions
The results show that allowing for conditional, within-year responses to weather reduces the frequency of crop switching between years by 24% and increases expected income by 10% compared to the case where conditional responses are not permitted.

These results further support the existing literature that highlight the importance of including dynamic responses in farming (Antle, 1983; Mjelde, Dixon, and Sonka, 1989; Rosenzweig and Udry, 2014; Wu, 2000). Additionally, the differences in model solutions when responses to stochastic events during the year are included show that even in the case when research is concerned with analyzing decisions over long horizons, ignoring the decisions available to farmers within the year leads to different and insufficient answers.

Comparison of the results of the second and third scenarios reveals that the higher fertilization rates recommended by the NCARE Extension service are optimal and raise the question of why farmers do not apply more, as results show higher profits and lower variance of outcomes. We speculate that the answers lie in either capital constraints or farmer' misperceptions of fertilizer use.

Sources
Antle, John M. 1983. "Sequential Decision Making in Production Models." *American Journal of Agricultural Economics* no. 65 (2):282-290. doi: 10.2307/1240874.
Burt, Oscar R., and John R. Allison. 1963. "Farm Management Decisions with Dynamic Programming." *Journal of Farm Economics no.* 45 (1):121-136. doi: 10.2307/1235923.
El-Nazer, Talaat, and Bruce A. McCarl. 1986. "The Choice of Crop Rotation: A Modeling Approach and Case Study." *American Journal of Agricultural Economics* no. 68 (1):127-136. doi: 10.2307/1241657.
Farquharson, Robert J., Oscar J. Cacho, John D. Mullen, and Graeme D. Schwenke. "An Economic Approach to Soil Fertility Management for Wheat Production in North-Eastern Australia." *Agricultural Economics* 38, no. 2 (March 1, 2008): 181–92. doi:10.1111/j.1574-0862.2008.00292.x.
Jones, Randall, Oscar Cacho, and Jack Sinden. 2006. "The Importance of Seasonal Variability and Tactical Responses to Risk on Estimating the Economic Benefits of Integrated Weed Management." *Agricultural Economics* 35, no. 3: 245–56. doi:10.1111/j.1574-0862.2006.00159.x.
Keating BA, Carberry PS, Hammer GL *et al. (*2003*)* An overview of APSIM, a model designed for farming systems simulation. *European Journal of Agronomy, 18, 267–288.*
Livingston, Michael, Michael J. Roberts, and Yue Zhang. 2014. "Optimal Sequential Plantings of Corn and Soybeans Under Price Uncertainty." *American Journal of Agricultural Economics*. doi: 10.1093/ajae/aau055.
Miranda, Mario J., and Paul L. Fackler. 2002. Applied Computational Economics and Finance. Cambridge, Massachusetts: The MIT Press.
Mjelde, James W., Bruce L. Dixon, and Steven T. Sonka. 1989. "Estimating the Value of Sequential Updating Solutions for Intrayear Crop Management." *Western Journal of Agricultural Economics* no. 14 (1):1-8. doi: 10.2307/40988003.
Rosenzweig, Mark R., and Christopher Udry. 2014. "Rainfall Forecasts, Weather, and Wages over the Agricultural Production Cycle." *American Economic Review* no. 104 (5):278-83.
Semenov, Mikhail. 2010. "The Use of Multi-Model Ensembles from Global Climate Models for Impact Assessments of Climate Change." *Climate Research* no. 41:1-14.
Wu, JunJie. (2000). "Optimal Weed Control under Static and Dynamic Decision Rules." *Agricultural Economics* 25, no. 1: 119–30. doi:10.1111/j.1574-0862.2001.tb00239.x.

Figures and Tables

**Table 1. Cropping Choices**

Choices at Planting		Top- Dressing 60 Days after Planting	Harvesting at Maturity
Crop Type	*Fertilizer- DAP (kg/ha.)*	*Fertilizer- Urea (kg/ha.)*	*Harvesting Method*
Barley (Rum)	0	0	Mechanical harvest then graze
Barley (Steptoe)	50	40	Manual harvest then graze
Fallowing	100		Mechanical harvest
Wheat			Manual harvest

*Figure 1. Results of Typical Static Within-Year DP Crop Model*
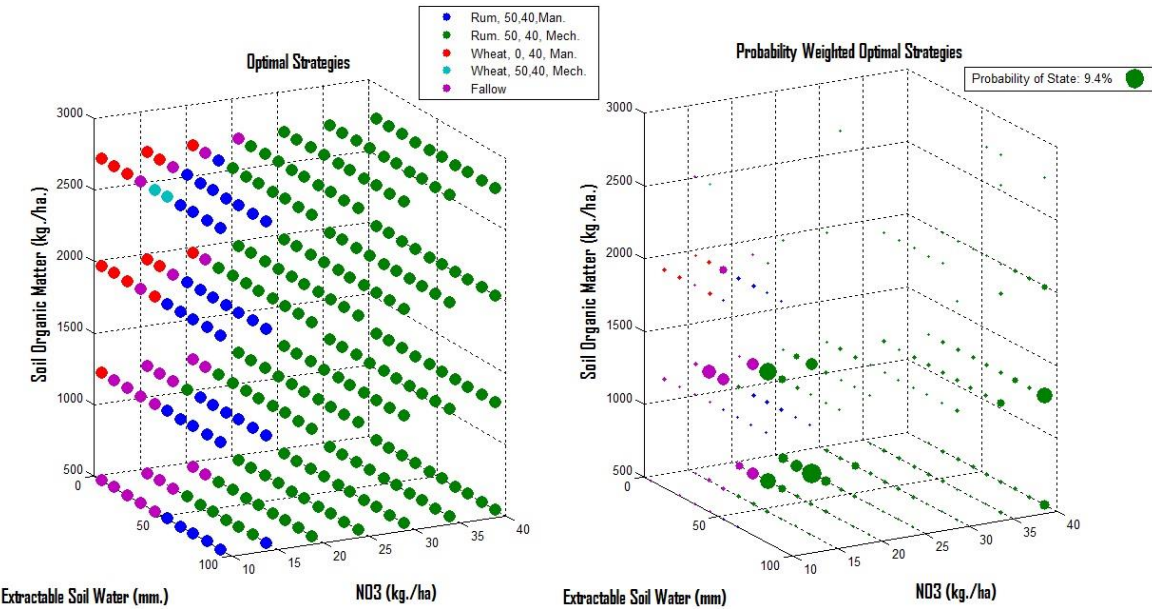
Notes: Size of dot in the right-hand figure indicates steady-state probability of soil state.

Figure 2. Results with Conditional Stochastic Responses
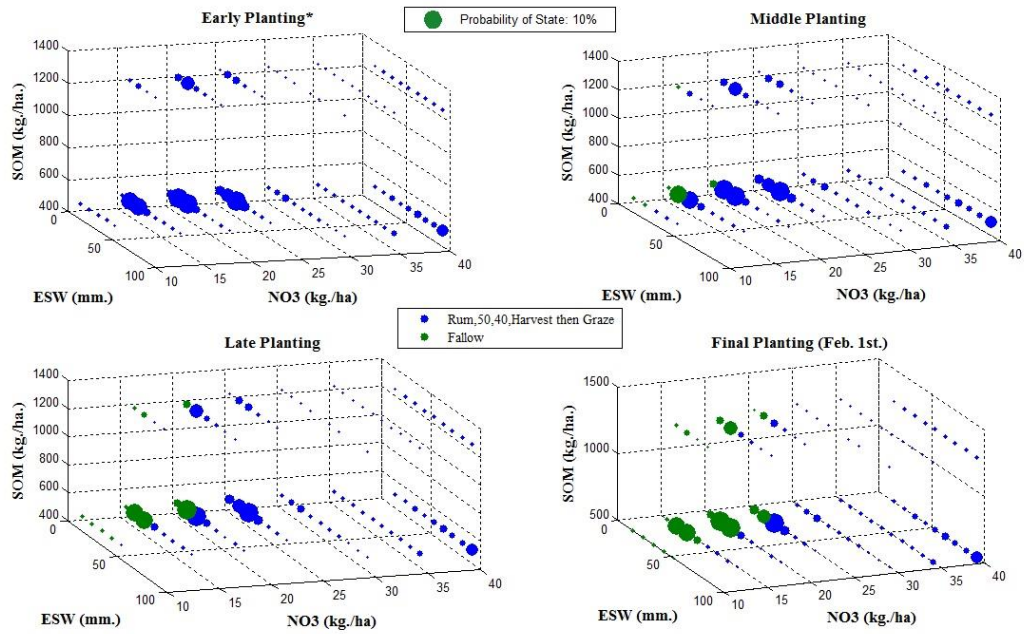
Notes: Size of dot in each sub-figure indicates steady-state probability of soil state.

Figure 3. Results with Conditional Stochastic Responses and Agronomic Recommended Fertilizer Levels
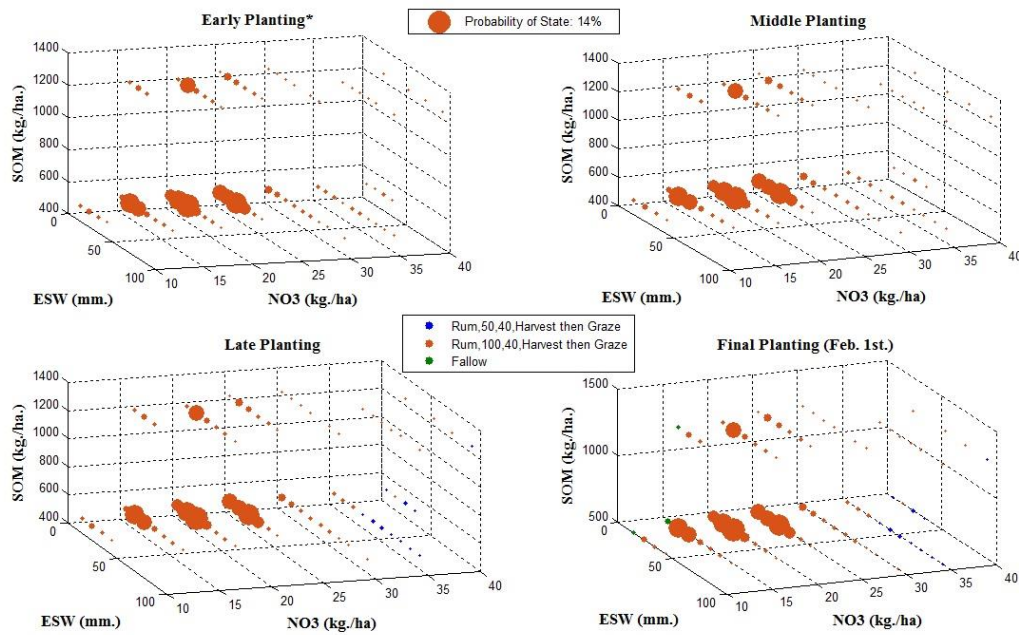
Notes: Size of dot in each sub-figure indicates steady-state probability of soil state.

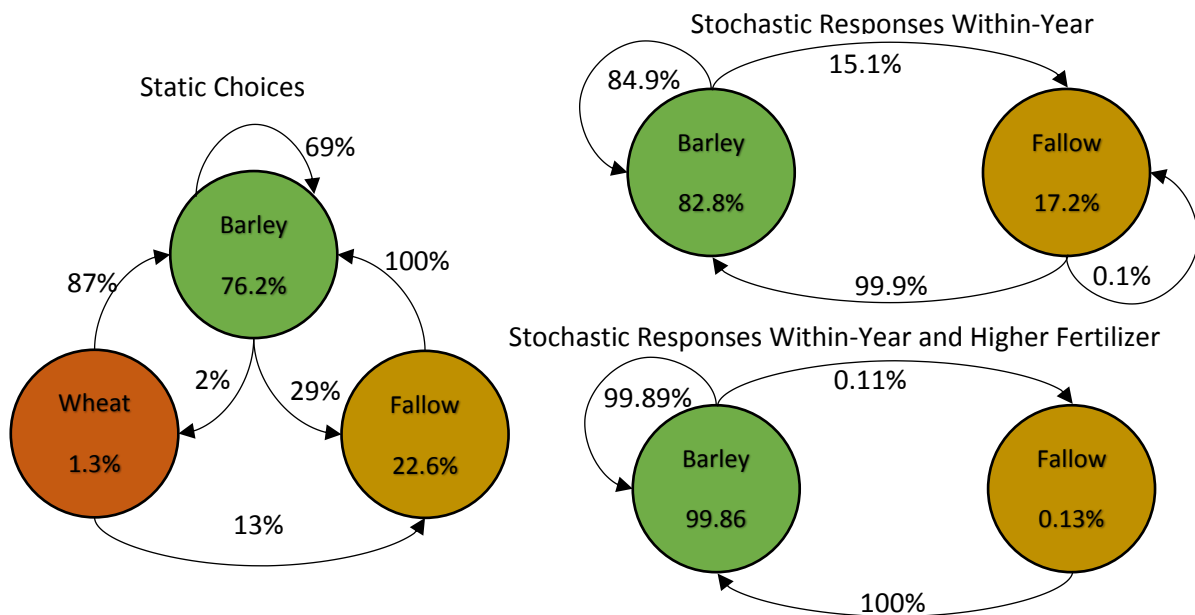## Figure 4. Comparison of Results across Models: Rotational Differences

Static Choices

Stochastic Responses Within-Year

Stochastic Responses Within-Year and Higher Fertilizer

Table 2. Comparison of Results across Models: Steady-state Solutions

Choices	Weighted Value Function (JD/ha)	ESW (mm/ha)	NO3 (kg/ha)	SOM (kg/ha)	Number of Recurrent States
Static	9,769	35.22	25.23	922.68	162
Stochastic Response	10,677	28.61	23.70	621.15	99
Stochastic Response + Agron. Recom.	12,453	20.32	21.09	601.06	78