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

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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

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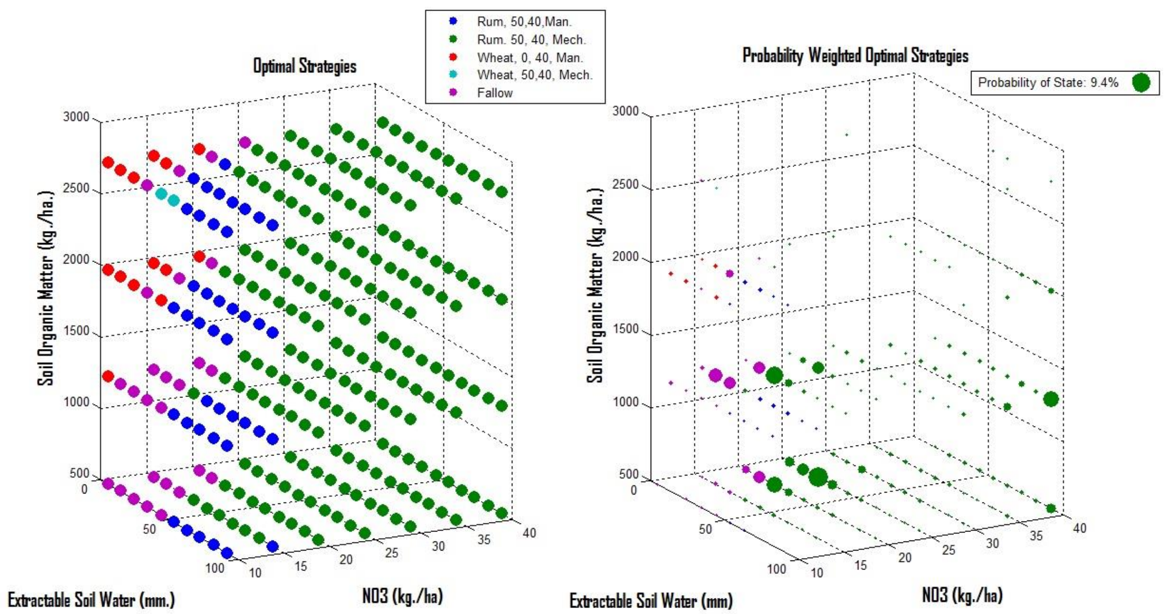
Figures and Tables

Table 1. Cropping Choices

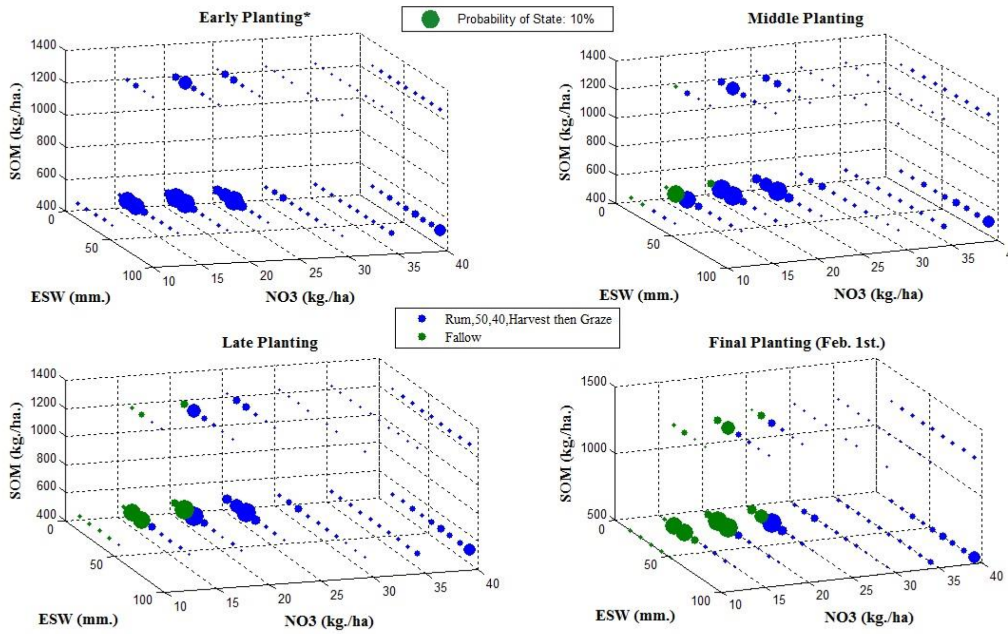
Choices at Planting		Top- Dressing 60 Days after Planting	Harvesting at Maturity
Crop Type	***Fertilizer- DAP (kg/ha.)***	***Fertilizer- Urea (kg/ha.)***	***Harvesting Method***
Barley (Rum)	0	0	Mechanical harvest then graze
Barley (Steptoe)	50	40	Manual harvest then graze
Fallowing	100		Mechanical harvest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

Figure 1. Results of Typical Static Within-Year DP Crop Model



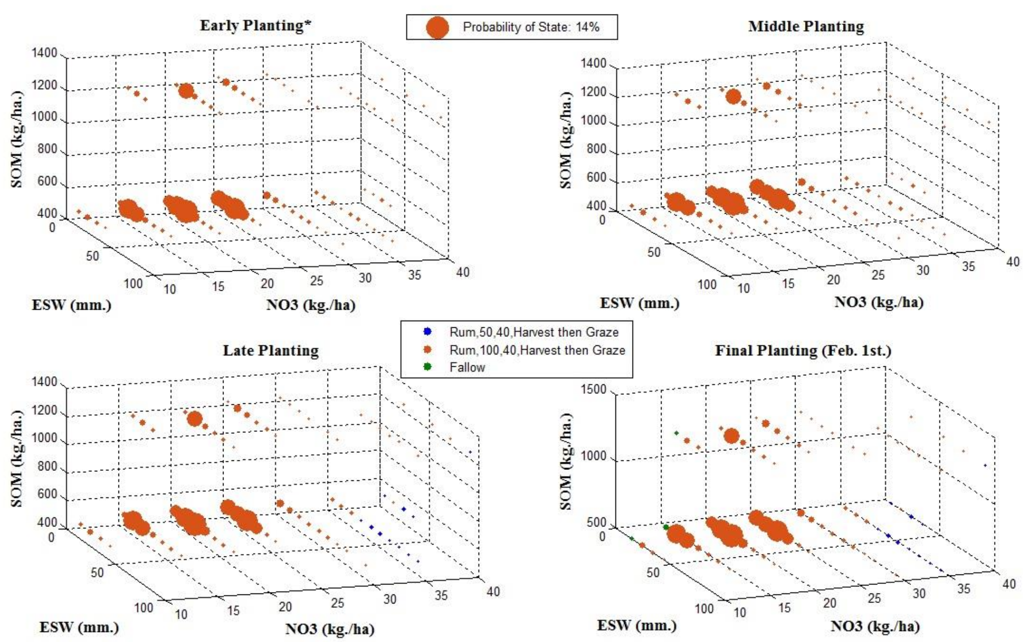
Notes: Size of dot in the right-hand figure indicates steady-state probability of soil state.

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

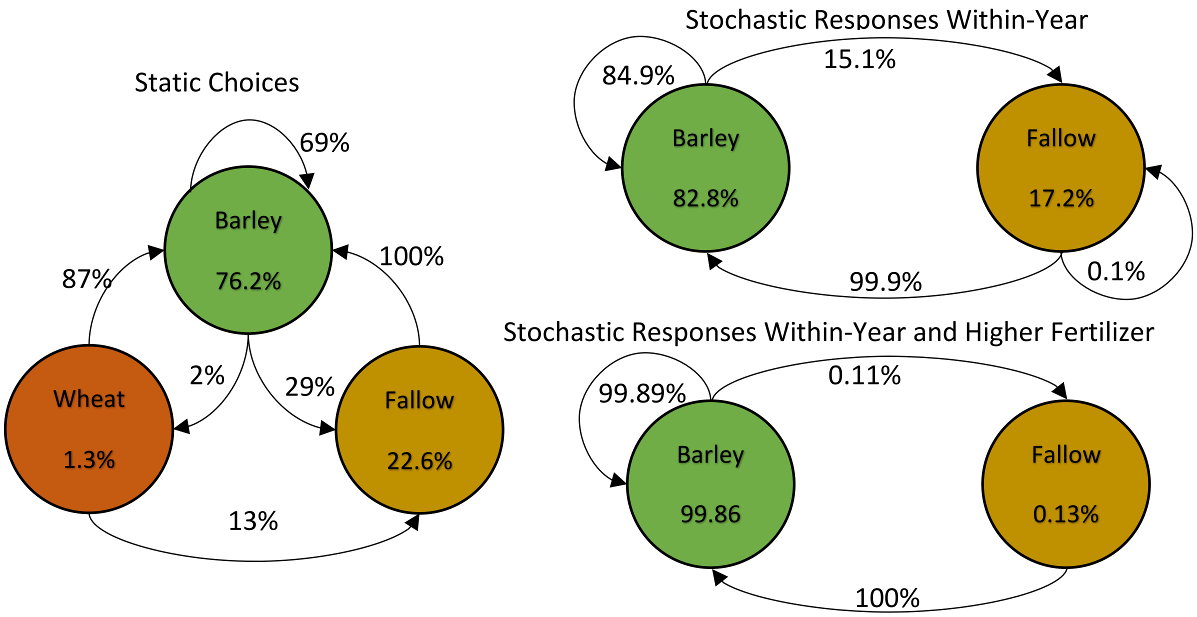


Table 2. Comparison of Results across Models: Steady-state Solutions

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