THE PERSISTENCE OF DROUGHT IMPACTS ACROSS GROWING SEASONS: A DYNAMIC STOCHASTIC ANALYSIS

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Abstract

Agricultural producers throughout much of the United States experienced one of the most severe droughts in the last 100 years during the years 1999-2006. The prolonged nature of this drought highlights a need to better understand the impacts and management of drought across growing seasons, rather than just within a growing season. Producers express specific concern about the tendency of drought impacts to persist even after drought itself has subsided. The persistence of drought impacts has received limited attention in the economics literature. The objectives of this study are two-fold: 1) to determine whether inter-year dynamics, in the form of agronomic constraints and financial flows, can cause persistence of a drought's impact in years subsequent to the drought, and 2) to determine whether the impact of one year of drought can alter the impact of a subsequent year of drought. A multi-year, dynamic and stochastic decision model is developed in a discrete stochastic programming framework and solved to address the objectives. The structure and parameters of the farm-level model are based on irrigated row crop farms in eastern Oregon, USA. Analysis of the model's solution reveals the following results: 1) the impact of a drought can persist long after the drought subsides, and 2) the impact of one year of drought can alter the impact of a subsequent year of drought. Potential implications for the administration of drought-related assistance are discussed briefly.

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Keywords

Drought, preparedness, response, uncertainty, dynamics, discrete stochastic programming, agriculture, irrigation, eastern Oregon, row crops, crop rotation

1 Introduction

Climate variability is a major source of uncertainty for agriculture in the United States, generating an expected annual loss of $80-95 billion (EASTERLING AND MENDELSOHN, 2000). Drought is one manifestation of climate variability that continues to challenge agriculture, particularly in the semi-arid regions of the western United States, where the frequency of drought is high (WILHITE AND RHODES, 1993). Agricultural producers throughout much of the United States experienced one of the most severe droughts in the last 100 years during the years 1999-2006 (HEIM AND LAWRIMORE, 2006). At the peak of the drought, in 2004, two-thirds of the western United States was affected (HEIM AND LAWRIMORE, 2006). The prolonged nature of this drought highlights a need to better understand the impacts and management of drought across growing seasons, rather than just within a growing season. Producers express specific concern about the tendency for drought impacts to persist even after the drought itself has subsided.

The persistence of drought impacts has received limited attention in the economics literature. THOMPSON AND POWELL (1998) mention in passing that the physical and financial flows between years in their livestock model capture the lagged impacts of drought. They do not elucidate, however, on the nature, degree or implications of these lagged impacts. CLAWSON ET. AL (1980) recognizes the dynamic nature of drought impacts, noting that "the form of the recovery from one drought may greatly affect the flexibility to deal with the inevitable next drought." Other studies incorporate inter-year dynamics into their drought models; however, none focus on the persistence of drought impacts (GARRIDO AND GOMEZ-RAMOS, 2000; HAOUARI AND AZAIEZ, 2001; IGLESIAS ET AL., 2003); (TOFT AND O'HANLON, 1979; WEISENSEL ET AL., 1991).

The objectives of this study are two-fold: 1) to determine whether inter-year dynamics, in the form of agronomic constraints and financial flows, can cause persistence of a drought's impact in years subsequent to the drought, and 2) to determine whether the impact of one year of drought can alter the impact of a subsequent year of drought. A multi-year, dynamic and stochastic decision model is developed in a discrete stochastic programming framework and solved to address the objectives. The structure and parameters of the farm-level model are based on irrigated row crop farms in eastern Oregon, USA. Analysis of the model's solution reveals the following results: 1) the impact of a drought can persist long after the drought subsides, and 2) the impact of one year of drought can alter the impact of a subsequent year of drought. Potential implications for the administration of drought-related assistance are discussed briefly.

2 Modelling Approach

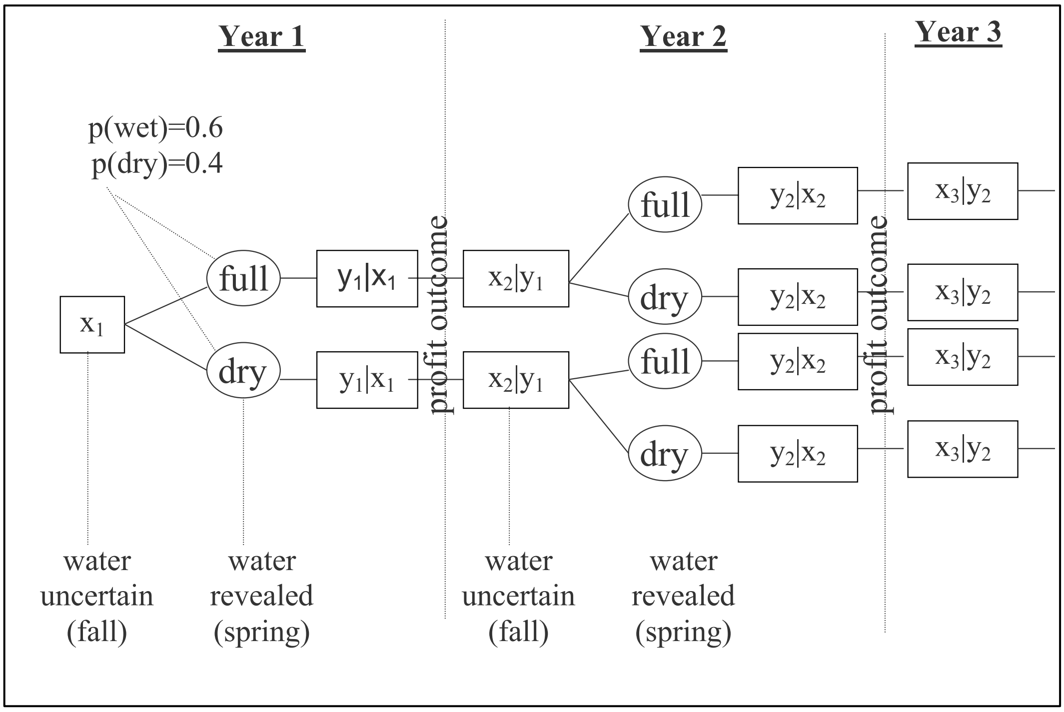
2.1 Primer on Discrete Stochastic Programming

Discrete stochastic programming (DSP) is the mathematical programming framework used in this study to build the farm-level decision model. DSP was introduced by COCKS (1968) as a method for solving linear programming problems that include any number of random variables as coefficients in the constraints and/or the objective function. The ability to include random coefficients in constraints and the objective function enables a modeller to account for the timing of decisions relative to the timing of information discovery. Specifically, a modeller can represent a multi-stage problem where decisions are made both before and after random variables are realized. Decisions made before the random variables' values are revealed are known as "first-stage" activities. Decisions or calculations made after random variables' values are revealed are known as "second-stage" or "recourse" activities. The number of stages in a DSP problem depends on the number of decision/information/recourse decision cycles that occur during the decision-making process.

RAE (1971), in one of the first applications of discrete stochastic programming to agriculture, illustrates how DSP captures this decision process.

The general goal of DSP is to choose first-stage activity levels that maximize current benefits (or minimize current costs) plus the expected benefit (or expected cost) of second-stage activities. The DSP solution indicates optimal first-stage activity levels, as well as optimal second-stage activity levels for each possible realization of the random variables. This approach, at least in its discrete form, is reminiscent of decision tree analysis (HARDAKER ET AL., 1997: 198), as illustrated in figure 1.

Figure 1: Decision tree representation of discrete stochastic programming.



*) Fall cropping activities (x_t) are chosen given an uncertain spring water supply. The spring water supply is then revealed (full or dry), after which spring cropping activities (y_t) are implemented. To identify optimal x_1, the model must simultaneously identify optimal activities for all subsequent decision stages.

Source: Own representation.

2.2 The Empirical Model

The structure and parameters of the empirical DSP model are based on irrigated row-crop farms of the Vale Oregon Irrigation District in Malheur County, Oregon, USA. The study area is located at an elevation of 670 meters (2,200 feet). Average annual precipitation is approximately 250 millimetres (9.8 inches), thus irrigation is required for most crops. Snowmelt captured and stored in reservoirs is the primary source of irrigation water. Crops found in the study area and incorporated in the model include alfalfa hay, winter wheat, sugar beets, potatoes, onions, grain corn and silage corn. Several alternative irrigation technologies are also used in the study area and model, including furrow, sprinkler and drip irrigation. Deficit irrigation, the practice of intentionally providing less water than is needed to maximize crop yield, is also practiced in the study area and included as a management option in the model. The structure of the decision model, which is based on farming practices observed in the study area, is described next and also illustrated in figure 1.

In the fall of each year (i.e. stage 1), the model (henceforth referred to as the producer) chooses the number of acres to plant to winter wheat, the number of acres to prepare for onions, potatoes, and sugar beets, the irrigation system to be used, and the number of acres to leave unplanted and unprepared. At the time fall decisions are made, the water supply for the upcoming growing season is uncertain; only the subjective probability distribution is known. Fall decisions therefore represent the first stage of the DSP model.

Information enters the DSP model decision framework in early spring (i.e. between stage 1 and 2) when a water supply forecast becomes available. The forecast is assumed to perfectly predict the growing season's water supply, which is a simplifying assumption. Upon receiving these forecasts, and subject to constraints created by their fall decisions, the producer makes their spring decisions, which represent stage 2 (or the recourse stage) of the DSP model. Spring decisions enable the producer to adjust their crop plan in response to the water supply forecast. The producer decides whether to plant or leave fallow any fields that were left unprepared in the fall. They also decide whether to follow through with or abandon each fall-prepared or fall-planted field; abandoned fields can either be fallowed for the season or converted to corn, which is the only crop that cultivated without fall fieldwork. For each field that is kept in cultivation, the producer chooses the proportion of the crop water requirement to provide, i.e. the degree of deficit irrigation. Profit for the crop year (i.e. from fall through summer harvest) is then calculated, and the producer proceeds to the start of the next crop year.

Intra-year dynamics clearly exist in this farm system; specifically, fall decisions constrain spring decisions. The number of winter wheat fields kept in the spring, for example, cannot exceed the number of fields planted in the fall. However, there are also inter-year dynamics in the system; that is, decisions and outcomes from previous years affect decisions in future years. Agronomic practices that producers in the study area use to minimize pest and disease outbreaks are the primary source of inter-year dynamics. Onions, for example, are typically planted only once every six years in individual fields. Wheat is typically not planted two consecutive years in individual fields. Alfalfa, if kept through the first year, is typically kept for four years to enhance soil quality. Crop choice for individual fields in a particular year clearly affects the producer's crop options in subsequent years. In the case of sugar beets and alfalfa, and onions and potatoes, crop choice in year t has the potential to affect options through years t+3 and t+5, respectively.

The dynamics in this farm system require producers to be forward looking not only because fall decisions affect spring decisions, but because decisions in the current crop year affect those in future years. To capture inter-year dynamics, the decision model spans a six-year period (the longest period that a single agronomic constraint spans); two decision stages occur within each year. To identify optimal first-year, first-stage decisions in the presence of uncertainty and intra- and inter-year dynamics, the model must also identify optimal activities for all subsequent decision stages and years of all potential water supply outcomes. The equations of the DSP model are presented and explained next.

$$\max_{x,y} \; E_s \Pi(x, y; s) \tag{1}$$

s.t.

$$Ax = b \tag{2}$$

$$Dy = e \tag{3}$$

$$Mx + Ny = g \tag{4}$$

$$x, y \geq 0, \text{ with} \tag{5}$$

s = A random vector that represents water supplies over a 6-year planning horizon. Each realization of *s* consists of 6 components (s1 s2 s3 s4 s5 s6), which indicate the state of nature (water supply category) revealed in each of the six years. That is, s1 represents the state of nature revealed in year 1, s2 the state of nature revealed in year 2, etc. Assuming 2 possible states of nature (Dry or Full) in each of 6 years, 64 six-year water supply scenarios are possible. Scenarios range from [Dry Dry Dry Dry Dry Dry] to [Full Full Full Full Full Full] including every combination between. The scenario [Dry Dry Full Full Full Full] indicates (from left to right) that the state of nature revealed in year 1 is Dry, year 2 is Dry, year 3 is Full, etc. Each state of nature has a probability of occurrence within any given year, denoted pr(Dry) or pr(Full). The state of nature in any one year is assumed independent of the state of nature in any other year, based on an autocorrelation analysis of historical streamflow data. Therefore, the joint probability of a particular six-year water scenario is the product of the probabilities of the states of nature that occur each year. For example, pr([Dry Dry Full Full Full Full]) = pr(Dry)*pr(Dry)*pr(Full)* pr(Full)*pr(Full)*pr(Full). Historical water allotment data and Gaussian quadrature analysis (FEATHERSTONE ET AL., 1993; MILLER AND RICE, 1983; PRECKEL AND DEVUYST, 1992) were used to assign quantity of water and probability to each state of nature.

x = A vector containing fall crop decision variables for each year of the planning horizon. Example element: $x_{3,f,c,i,s1,s2}$, which indicates for the fall of year 3, that field f is prepared for or planted to crop c, under irrigation technology i, given the states of nature revealed in past years 1 and 2. Each element of x is a binary variable, taking on a value of 0 (if the crop/irrigation combination (c,i) is not chosen for field f) or 1 (if the crop/irrigation combination (c,i) is chosen for field f). Each field may also be left "open," implying that it is neither prepared for nor planted to any crop.

y = a vector of spring crop decision variables for each year of the planning horizon. Example element: $y_{3,f,c,i,w,s1,s2,s3}$, which indicates for the spring of year 3, that field f is planted to crop c in the spring of year 3, under irrigation technology i, and deficit irrigation category w, given the states of nature revealed in past years 1, 2, and the present year 3. Each element of y is a binary variable, taking on a value of 0 (if the crop-irrigation-deficit combination (c,i,w) is not chosen for field f) or 1 (if the crop-irrigation-deficit combination (c,i,w) is chosen for field f). Each field may also be "fallowed," in which case it is either abandoned (if prepared or planted in the previous fall), or simply never planted (if left open in the previous fall).

$\Pi(x, y; s)$ = A vector containing the profit outcome for each water scenario. An individual element of the vector is the discounted stream of profit that optimal activities *x* and *y* generate over the 6-year period in which they occur, for a particular water scenario. Terminal land rental values, which are a function of activities in the 6-year decision period, are also included in the profit stream.

A, D = Matrices of coefficients that describe fall and spring activities' resource use.

b, e = Vectors of resource availability, such as land and water, which vary by state of nature for some resources.

M, N = Matrices of coefficients that relate activities in different stages to each other (intra- and inter-year rotation constraints).

g = A vector of parameters that, with *M* and *N* above, define relationships between activities in different stages.

In summary, the above discrete stochastic programming model maximizes the expected stream of profit over a 6-year planning horizon. The expectation is taken over water supply, *s*, which is assumed to have a discrete probability distribution over a small number of pre-defined categories (e.g. dry and full). Choice variables are contained in the vectors *x* and *y*. Vector *x* includes fall cropping activities, which are chosen under an uncertain future water supply. Vector *y* includes spring cropping activities, which are chosen after water supply is revealed. Fall and spring activities are chosen for each year of the six-year planning horizon, for each water supply scenario, (e.g. [Full Full Full Dry Dry Dry]). Sixty-four water supply scenarios are possible. Fall and spring activities are constrained by resource availability, as expressed in equations (2) and (3). Equation (4) describes dynamic interactions in the cropping system, including how fall activities restrict spring activities (intra-year dynamics), and how activities in a particular year restrict activities in subsequent years (inter-year dynamics).

The timing of decisions relative to the availability of water supply information is an essential feature of the DSSP model. It is assumed in this model that past water supply is known, but future water supply is uncertain. Specifically, fall cropping activities (x_t) are chosen before the water supply for the upcoming growing season is known, and before the water supplies for future growing seasons are known. Water supply for the upcoming growing season is revealed in early spring, after which spring cropping activities (y_t) are chosen. Note that although the water supply for the upcoming season is revealed in the spring, the water supplies in future growing seasons remain uncertain. This sequence of events (choose x_t, water supply is revealed, choose y_t) is repeated in each year of the six-year planning horizon.

Intra- and inter-year dynamics between cropping activities require the producer to be forward-looking to make optimal decisions. Future impacts of current decisions are challenging to identify, however, because future water supplies are uncertain. The following example illustrates this point. Suppose, for simplicity, that the planning horizon is a single year, within which fall decisions are made given an uncertain water supply, and spring decisions are made given a certain water supply. When selecting fall activities, the producer must consider the impact on spring activities in the following two cases: 1) the spring allotment is revealed to be full, and 2) the spring is revealed to be dry. A particular set of fall activities might maximize profit in the event of a full allotment, but not a dry spring, or vice versa. In contrast, the optimal set of fall activities will, by the definition of "optimal" in this dissertation, maximize expected profit over both water scenarios. That is, the producer must select fall activities based on their performance in each possible water scenario, and the probability of each scenario.

A solution to this two-stage, single-year problem consists of one set of optimal fall activities, and two sets of optimal spring activities, one each for a full versus dry spring allotment. The producer implements the fall plan, and after the water supply is revealed as full or dry, the producer implements the corresponding spring plan. Suppose that the producer knows, prior to making their fall decision, that the allotment will be full. The resulting set of optimal fall activities would likely differ from the set derived under uncertainty.

When this model is expanded from one year to two, the producer identifies one set of optimal "fall year 1" activities, two sets of optimal "spring year 1" activities, two sets of optimal "fall year 2" activities, and four sets of optimal "spring year 2" activities (figure 1). The producer, in choosing their activities for fall year 1, considers that four water supply scenarios are possible over the two-year period: [Full Full], [Full Dry], [Dry Full], and [Dry Dry]. In addition to choosing a plan for fall year 1, the producer selects activities for each stage of every possible water supply scenario. In reality, the producer will update year 2 plans once the outcome of year 1 is realized, in order to make full use of information gained in year 1, and to look six years into the future before choosing a year 2 plan. The plan made for year 2 in the fall of year 1 should therefore be interpreted as an estimate of the optimal year 2 plan.

Two states of nature and a six-year planning horizon are assumed in the empirical model, so 64 unique water scenarios, and potentially 64 unique six-year crop plans exist. Once a crop plan is determined for each stage (fall and spring) of each year of each water supply scenario, a discounted stream of profit is calculated for each scenario (i.e. for each branch of the decision tree). Expected profit over all possible water supply scenarios is then calculated, given each scenario's probability of occurrence.

The DSP model is constructed in the software program GAMS (General Algebraic Modeling System). The explicit equations of the DSP model are provided and explained in the appendix. The model is solved in GAMS using the commercially available solution algorithm package CPLEX. The optimal crop plans and profit for various water supply scenarios (i.e. for various branches on the decision tree) are compared to determine whether the impact of a drought persists in years subsequent to the drought.

3 Results

3.1 Persistence of Drought Impacts

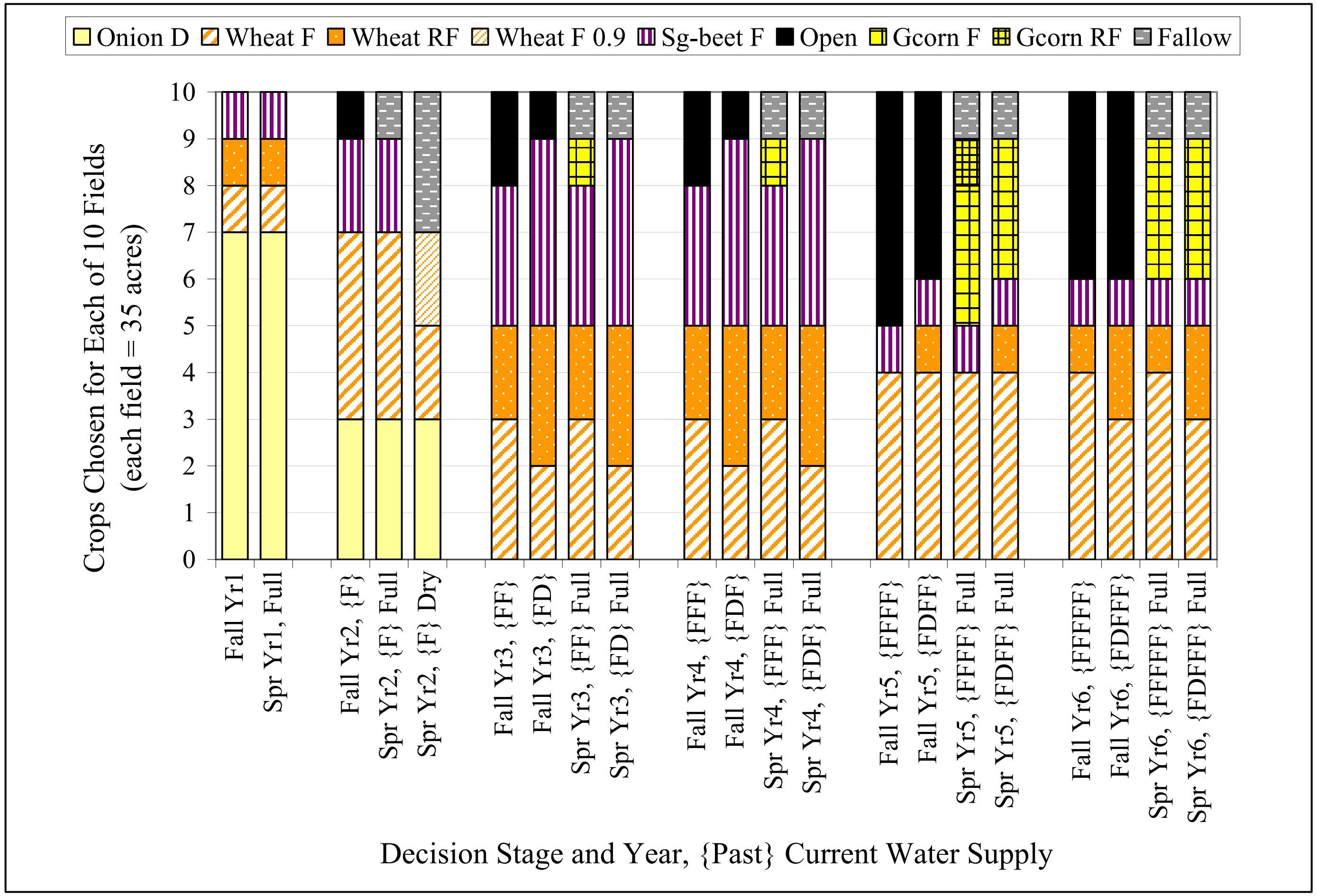
The crop plan and profit associated with two water supply scenarios (i.e. two branches on the decision tree) are compared to determine whether the impact of a drought persists after the drought subsides. Specifically, the following two water supply scenarios are compared to determine whether a year 2 drought (i.e. a drought in the second year of the six-year crop plan) affects cropping activities and profit in subsequent years: (a) [Full Dry Full Full Full Full] and (b) [Full Full Full Full Full Full].

The impact of drought in the year in which it occurs is examined first, because a producer's response to drought is one potential determinant of future impacts. Response to a year 2 drought includes fallowing two fields that were prepared in the fall for sugar beets, and deficit irrigating two wheat fields (figure 2). Net revenue in year 2 is $25,641 less than if no drought occurs (table 1). The loss of net revenue is attributable to changes in both total revenue and total cost. Total revenue decreases because sugar beets that are not planted cannot be sold, and because yield in the deficit irrigated wheat fields is less than if fully irrigated. Total cost decreases because spring planting costs for sugar beets are not incurred. Considered next is whether inter-year crop dynamics cause a single-year drought to generate impacts in subsequent years.

Differences in the two scenarios' profit and cropping activities subsequent to the drought would indicate that the impacts of drought are not isolated to the year in which it occurs. The two scenarios' profits in years subsequent to the drought are, in fact, not equal (table 1). One might expect profit in years subsequent to the drought to be lower in scenario (a) than in scenario (b) because less profit in year 2 implies less earned interest in subsequent years. Scenario (a)'s profit is indeed lower in year 6, and the next six years, which simply capture terminal values. Profit in years 3 through 5, however, is higher for scenario (a) than scenario (b). This is because drought affects profit in subsequent years not just through reductions in earned interest, but also through changes in cropping activities.

The two scenarios' cropping activities differ in years subsequent to the drought (figures 2 and 3). Drought's role in these differences is clear for years 3 and 4. The producer, having abandoned two sugar beet fields during the year 2 drought, reattempts those fields in subsequent years. Specifically, sugar beet production is increased from three to four fields in both years 3 and 4 (note: scenario (b)'s activities serve as the reference point). This requires them, however, to adjust other cropping activities as well, because water is insufficient, ceteris paribus, to support an extra field of sugar beets. Adjustments include removing grain corn from the crop plan in years 3 and 4 to accommodate sugar beets, and using reuse furrow on one additional field of wheat. The above adjustments to the crop plan in response to drought result in higher profit in years 3 and 4 than in scenario (b) (table 1). Profit lost in year 2 is therefore partially recaptured in years 3 and 4. We conclude that drought in year 2, or more precisely, the producer's response to the drought, generates impacts not only during the year in which drought occurs, but also in subsequent years. An economic analysis that focuses on activities during the year of drought alone will fail to capture this post-drought rebound.

Figure 2: Cropping impacts of a year 2 drought.



*) A stage-by-stage comparison of optimal cropping activities for scenarios [Full Full Full Full Full Full] and [Full Dry Full Full Full Full] of the base case. Crop Key: F = furrow, RF = reuse furrow, D = drip, 0.9 = 90% of crop's irrigation requirement is provided.

Source: Own representation.

Table 1: Impact of a year 2 drought on undiscounted profit.

	Undiscounted Profit (US$)												
	6-Year Period of Active Production						6-Year Period of Terminal Values						
Scenario	**Yr1**	**Yr2**	**Yr3**	**Yr4**	**Yr5**	**Yr6**	**Yr7**	**Yr8**	**Yr9**	**Yr10**	**Yr11**	**Yr12**	**Total**
(a)	74,121	26,257	32,727	35,018	22,946	23,054	160,052	108,683	69,362	74,217	79,413	84,972	790,823
(b)	74,121	51,898	30,180	32,293	19,885	25,764	161,453	110,183	70,966	75,934	81,249	86,937	820,863
(a)-(b)	0	-25,641	2,547	2,725	3,061	-2,710	-1,401	-1,499	-1,604	-1,717	-1,837	-1,965	-30,040

*) A year-by-year comparison of undiscounted profit for scenarios (a) [Full Dry Full Full Full Full] and (b) [Full Full Full Full Full Full] of the base case optimal solution.

Source: Own calculations.

Table 2: Impact of a year 3 drought on undiscounted profit.

	Undiscounted Profit (US$)												
	6-Year Period of Active Production						6-Year Period of Terminal Values						
Scenario	**Yr1**	**Yr2**	**Yr3**	**Yr4**	**Yr5**	**Yr6**	**Yr7**	**Yr8**	**Yr9**	**Yr10**	**Yr11**	**Yr12**	**Total**
(c)	74,121	51,898	6,820	25,102	32,415	28,844	160,407	109,064	69,769	74,653	79,878	85,470	798,439
(b)	74,121	51,898	30,180	32,293	19,885	25,764	161,453	110,183	70,966	75,934	81,249	86,937	820,863
(c)-(b)	0	0	-23,361	-7,191	12,530	3,080	-1,046	-1,119	-1,198	-1,281	-1,371	-1,467	-22,424

*) A year-by-year comparison of undiscounted profit for scenarios (b) [Full Full Full Full Full Full] and (c) [Full Full Dry Full Full Full] of the base case optimal solution.

Source: Own calculations.

Figure 3: Crops assigned to each field in each year of the six-year planning horizon (first row of each box reads from left to right, fields 1 to 5; second row reads from left to right, fields 6 to 10).

(i)

Year 1 [Full]				
O	O	SB	F	W
O	W	O	O	O

Year 2 [Full]				
F	W	O	SB	O
W	O	SB	W	W

Year 3 [Full]				
W	GC	W	W	W
SB	W	F	SB	SB

Year 4 [Full]				
SB	W	GC	F	SB
W	SB	W	W	W

Year 5 [Full]				
W	SB	W	W	GC
F	W	GC	GC	GC

Year 6 [Full]				
GC	W	SB	F	W
W	GC	W	GC	W

(ii)

Year 1 [Full]				
O	O	SB	F	W
O	W	O	O	O

Year 2 [Dry]				
F	W	O	**F**	O
W	O	**F**	W	W

Year 3 [Full]				
W	**SB**	W	W	**SB**
SB	W	**W**	**F**	SB

Year 4 [Full]				
SB	W	**F**	**SB**	**W**
W	SB	**SB**	W	W

Year 5 [Full]				
W	**F**	W	W	GC
GC	W	**W**	**SB**	GC

Year 6 [Full]				
GC	W	SB	**GC**	W
W	GC	**F**	**W**	W

*) Boxes on the left (column (i)) are for scenario (b) [Full Full Full Full Full Full]; boxes on the right (column (ii)) are for scenario (a) [Full Dry Full Full Full Full]. Key: O=onion, SB=sugar beet, W=wheat, GC=grain corn, F=fallow. Bold letters in column (ii) indicate fields whose crops differ from those in column (i).

Source: Own representation.

3.2 Subsequent Years of Drought

Multiple-year drought events have the potential, because of inter-year crop dynamics, to generate complex impacts on cropping activities and profit. The structure of the empirical DSP model enables us to study the impact of multi-year drought. A comparison of the following four scenarios is made to understand the potential impacts of a two-year drought occurring in years 2 and 3: (a) [Full Dry Full Full Full Full], (b) [Full Full Full Full Full Full], (c) [Full Full Dry Full Full Full], and (d) [Full Dry Dry Full Full Full].

A year 2 drought generates a loss of $30,040 in undiscounted profit (table 1). A year 3 drought generates a loss of $22,424 (table 2). If the impacts of these droughts were isolated within the year in which they occurred, two outcomes would be expected: 1) the profit impact of a two-year drought that occurs in years 2 and 3 should be approximately equal to the sum of the individual droughts' impacts ($52,464), and 2) the losses attributable to a year 3 drought should be the same regardless of whether it preceded by a dry or full year. The result, however, is that a two year drought generates a loss of $85,737 (table 3), which is much larger than the hypothesized loss of $52,464. Also, the impact of a year 3 drought is $55,697 when preceded by a year 2 drought (table 4), and only $22,424 when not preceded by drought (table 2).

These two results indicate that the impact of a year 3 drought depends on whether it was preceded by drought, or equivalently, that the impact of a year 2 drought depends on whether a drought is revealed in year 3. The results suggest, more generally, that the impact of a multi-year drought is more complex than the sum of its parts. This result also reinforces the previous subsection's conclusion that the impact of drought in a farm system that has inter-year dynamics can continue after the drought subsides.

The impact of a year 3 drought is larger when preceded by a year 2 drought because of the producer's response to the year 2 drought. Specifically, the producer attempts to recover from a year 2 drought by preparing four fields for sugar beets in the fall of year 3, rather than three fields (figure 2). When drought is revealed in the spring of year 3, the producer has to abandon three fields, rather than two (figure 4). Investments in fall field preparation are sunk, so the producer receives no return on a fall-prepared field that is later abandoned.

The above results are attributable to the model's inter-year agronomic constraints, which prevent the producer from continuously growing the same crop in a particular field. The producer, if forced to abandon a field of sugar beets in year t, for example, can replant the field to sugar beets in year t+1 without displacing sugar beets already planned for that field. This is because the field is eligible for sugar beets only once every five years. While replanting delays all future sugar beet crops on that field, the farm's total sugar beet acreage over the six-year crop plan is not reduced.

Table 3: Impact of a two-year drought (years 2 and 3) on undiscounted profit.

	Undiscounted Profit (US$)												
	6-Year Period of Active Production						6-Year Period of Terminal Values						
Scenario	**Yr1**	**Yr2**	**Yr3**	**Yr4**	**Yr5**	**Yr6**	**Yr7**	**Yr8**	**Yr9**	**Yr10**	**Yr11**	**Yr12**	**Total**
(d)	74,121	26,257	-2,091	26,596	30,101	22,026	157,454	105,904	66,388	71,035	76,007	81,328	735,126
(b)	74,121	51,898	30,180	32,293	19,885	25,764	161,453	110,183	70,966	75,934	81,249	86,937	820,863
(d)-(b)	0	-25,641	-32,271	-5,697	10,216	-3,738	-3,999	-4,279	-4,579	-4,899	-5,242	-5,609	-85,737

*) A year-by-year comparison of undiscounted profit for scenarios (b) [Full Full Full Full Full Full] and (d) [Full Dry Dry Full Full Full] of the base case optimal solution.

Source: Own calculations.

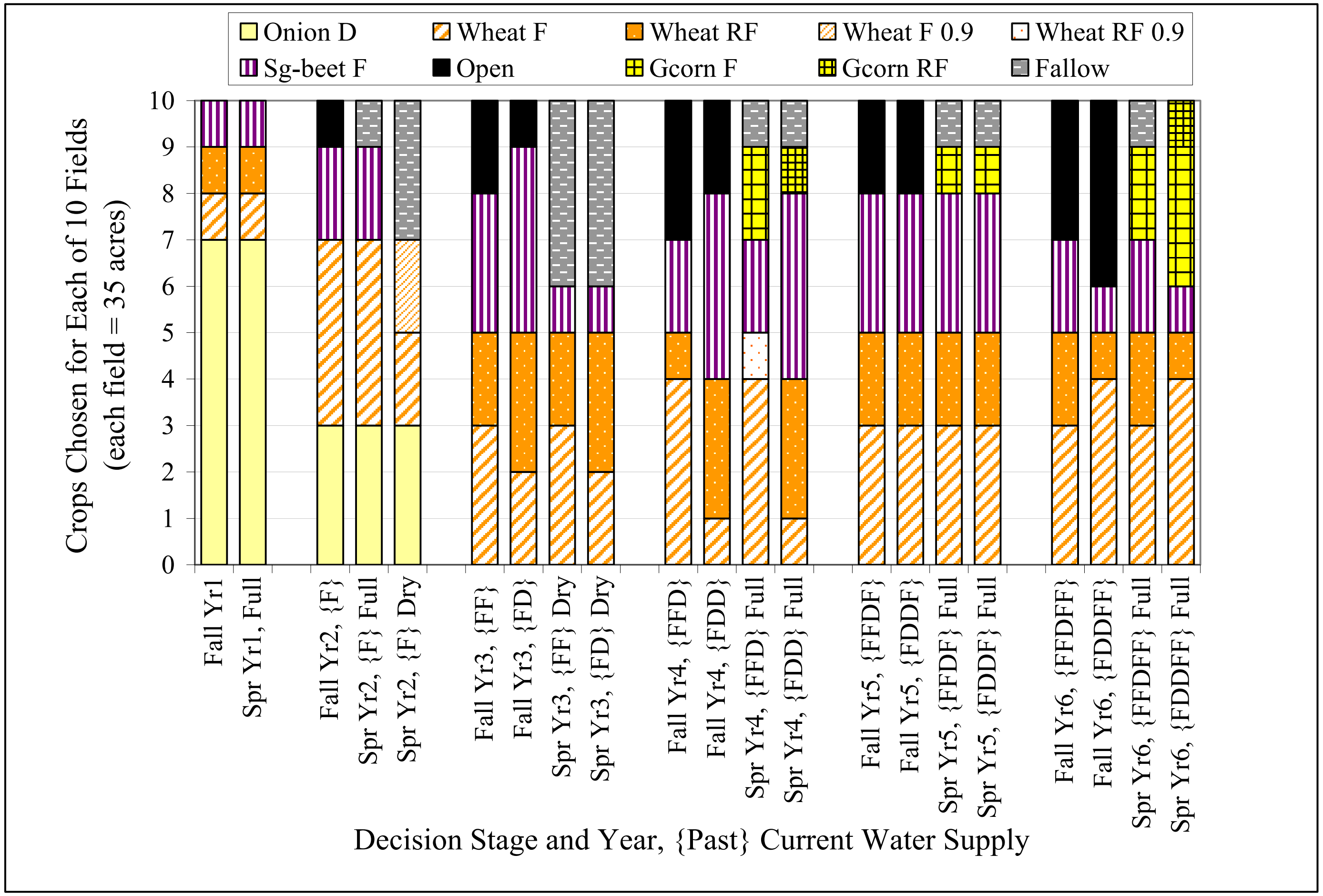
Table 4: Impact on undiscounted profit of a year 3 drought when preceded by a year 2 drought.

	Undiscounted Profit (US$)												
	6-Year Period of Active Production						6-Year Period of Terminal Values						
Scenario	**Yr1**	**Yr2**	**Yr3**	**Yr4**	**Yr5**	**Yr6**	**Yr7**	**Yr8**	**Yr9**	**Yr10**	**Yr11**	**Yr12**	**Total**
(d)	74,121	26,257	-2,091	26,596	30,101	22,026	157,454	105,904	66,388	71,035	76,007	81,328	735,126
(a)	74,121	26,257	32,727	35,018	22,946	23,054	160,052	108,683	69,362	74,217	79,413	84,972	790,823
(d)-(a)	0	0	-34,818	-8,422	7,155	-1,028	-2,598	-2,780	-2,974	-3,183	-3,405	-3,644	-55,697

*) A year-by-year comparison of undiscounted profit for scenarios (a) [Full Dry Full Full Full Full] and (d) [Full Dry Dry Full Full Full] of the base case optimal solution.

Source: Own calculations.

Figure 4: Cropping impacts of a year 3 drought when preceded by a full versus dry year 2.



*) A stage-by-stage comparison of activities for scenarios [Full Full Dry Full Full Full] and [Full Dry Dry Full Full Full] of the base case. Crop Key: F = furrow, RF = reuse furrow, D = drip, 0.9 = 90% of crop's irrigation requirement is provided.

Source: Own representation.

4 Discussion

The model's first result confirms agricultural producers' claim that the impact of a drought can persist long after the drought subsides, at least in the irrigated row crop farm modeled here. Agronomic constraints and financial flows, which generate inter-year dynamics, are the cause of persistence in this farm system. One consequence of this persistence is that drought in one year can intensify the profit impact of drought in subsequent years, which was the second result of this study. This result confirms CLAWSON ET. AL'S (1980) suggestion that the form of recovery from one drought might affect a producer's ability to deal with the next drought.

Both results have important implications for government assistance in the event of drought. Suppose a government official asks a producer, after enduring one year of drought, to report profit impacts of the drought. A producer in the study area could honestly answer that they do not yet know. The total impact of a drought will depend on water supplies in subsequent years. The producer will initially recover some of their loss if they receive a full allotment next year. In contrast, their loss will be larger if next year is also dry. Although producers likely prefer prompt assistance in the event of drought, program administrators should keep in mind that the total impact of a particular year of drought might not be felt for several years. They should also keep in mind that the impact of a multi-year drought can be more or less than the sum of its parts. The marginal profit impact of a year of drought was shown above, for at least one scenario, to be 150% larger when preceded by a year of drought. This result highlights the importance of evaluating the impacts of an individual year of drought in the context of preceding and subsequent years. Lastly, the results provide insights for future modelling efforts. Studies that ignore inter-year dynamics or limit the timeframe of their analyses to the years in which drought occurs are likely to misestimate drought's full impact.

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Appendix: Detailed equations of the DSP model

$$\operatorname*{Max}_{x,y} \; E_s \Pi(x,y;s) = \sum_s \rho_s \cdot \left[\begin{array}{l} \displaystyle\sum_{t=1}^{6} \left(\frac{1}{(1+d)^t} \pi_{t,s}(x_{t,s}, y_{t,s}) \right) \\ \displaystyle + \sum_{t=7}^{12} \left(\frac{1}{(1+d)^t} \pi_{t,s}(y_{t-6,s}, \ldots y_{6,s}) \right) \end{array} \right] \quad (6)$$

where for t =1,...,6

$$\pi_{t,s}(x_{t,s}, y_{t,s}) = \sum_c \sum_i \sum_w \left(\begin{array}{l} \displaystyle\sum_f FAC \cdot (p_c yld_{c,i,w} y_{t,f,c,i,w,s} \\ - j_{c,i} y_{t,f,c,i,w,s} - h_{c,i} x_{t,f,c,i,s}) \end{array} \right) \quad (7)$$

$$- fxd\cos t - r \cdot \left(\begin{array}{l} \displaystyle\sum_c \sum_i \sum_w \left(\sum_f FAC \cdot (j_{c,i} y_{t,f,c,i,w,s} + h_{c,i} x_{t,f,c,i,s}) \right) \\ + fxd\cos t - \pi_{t-1,s}(x_{t-1,s}, y_{t-1,s}) \end{array} \right)$$

and

$$yld_{c,i,w} = \max yld_{c,i} \cdot \left[1 - \left(ky_c \cdot \left(1 - \frac{w \cdot (ET\max_c - Ppt) + Ppt}{ET\max_c} \right) \right) \right] \quad (8)$$

where for t =7,...,12

$$\begin{array}{l} \pi_{t,s}(y_{t-6,s}, \ldots y_{6,s}) = RRate_{onion} \cdot EligOnion_{t,s}(y_{t-6,s}, \ldots y_{6,s}) \\ \qquad + RRate_{other} \cdot EligOther_{t,s}(y_{t-6,s}, \ldots y_{6,s}) \\ \qquad + \left(\displaystyle\sum_i NetRv_{alf,i,d1} \cdot EligAlf_{t,i,s}(y_{6,s}) \right) - fxd\cos t \\ \qquad - r \cdot \left(\displaystyle\sum_i \left(j_{alf,i} \cdot EligAlf_{t,i,s}(y_{6,s}) \right) + fxd\cos t - \pi_{t-1,s}(y_{t-6,s}, \ldots y_{6,s}) \right) \end{array} \quad (9)$$

subject to

$$\sum_c \sum_i \sum_w \sum_f w \cdot \left(\frac{ET\max_c - Ppt}{IrrEffic_i} \right) \cdot FAC \cdot y_{t,f,c,i,w,s} \quad (10)$$

$$\leq Water_{t,s} \cdot TotAcres \qquad \forall\ t, s$$

$$x_{t,f,c,i,s} = 0 \qquad \text{for some t,c,i,s} \quad \forall\ f \quad (11)$$

$$y_{t,f,c,i,w,s} = 0 \qquad \text{for some t,c,i,w,s} \quad \forall\ f \quad (12)$$

$$x_{t,f,c,i,s}, y_{t,f,c,i,w,s} = 0 \text{ or } 1 \qquad \forall\ t,f,c,i,w,s \quad (13)$$

$$\sum_i x_{1,f,wheat,i} + H6_{f,wheat} + H6_{f,barley} \leq 1 \qquad \forall\ f \quad (14)$$

$$\sum_i x_{1,f,sugbt,i} + H6_{f,sugbt} + H5_{f,sugbt} + H4_{f,sugbt} \quad (15)$$

$$+H3_{f,sugbt} \leq 1 \quad \forall \text{f}$$

$$\sum_i x_{1,f,onion,i} + H6_{f,onion} + H5_{f,onion} + H4_{f,onion} \quad (16)$$

$$+H3_{f,onion} + H2_{f,onion} \leq 1 \qquad \forall \text{ f}$$

$$\sum_i x_{1,f,potato,i} + H6_{f,potato} + H5_{f,potato} + H4_{f,potato} \quad (17)$$

$$+H3_{f,potato} + H2_{f,potato} \leq 1 \qquad \forall \text{ f}$$

$$\sum_i \sum_f x_{1,f,potato,i} \leq PotatoContract \quad (18)$$

$$\sum_i x_{1,f,alf2,i} = H6_{f,alf1} \qquad \forall \text{ f,i} \quad (19)$$

$$\sum_i x_{1,f,alf3,i} = H6_{f,alf2} \qquad \forall \text{ f,i} \quad (20)$$

$$\sum_i x_{1,f,alf4,i} = H6_{f,alf3} \qquad \forall \text{ f,i} \quad (21)$$

$$\sum_c \sum_i x_{1,f,c,i} + open_{f,1} = 1 \qquad \forall \text{ f} \quad (22)$$

$$\sum_w y_{1,f,fall,i,w,s} \leq x_{1,f,fall,i} \qquad \forall \text{ f,fall,i,s} \quad (23)$$

$$\sum_w y_{1,f,alf2,i,w,s} = x_{1,f,alf2,i} \qquad \forall \text{ f,i,s} \quad (24)$$

$$\sum_w y_{1,f,alf3,i,w,s} = x_{1,f,alf3,i} \qquad \forall \text{ f,i,s} \quad (25)$$

$$\sum_w y_{1,f,alf4,i,w,s} = x_{1,f,alf4,i} \qquad \forall \text{ f,i,s} \quad (26)$$

$$\sum_i \sum_w y_{1,f,gcorn,i,w,s} + H6_{f,gcorn} + H6_{f,scorn} \quad (27)$$

$$+H5_{f,gcorn} + H5_{f,scorn} \leq 2 \qquad \forall \text{ f,s}$$

$$\sum_i \sum_w y_{1,f,scorn,i,w,s} + H6_{f,gcorn} + H6_{f,scorn} \quad (28)$$

$$+H5_{f,gcorn} + H5_{f,scorn} \leq 2 \qquad \forall \text{ f,s}$$

$$\sum_i \sum_w y_{1,f,barley,i,w,s} + H6_{f,barley} + H6_{f,wheat} \leq 1 \qquad \forall \text{ f,s} \quad (29)$$

$$\sum_c \sum_i \sum_w y_{1,f,c,i,w,s} = 1 \qquad \forall \text{ f,s} \quad (30)$$

$$\sum_i x_{2,f,wheat,i,s} + \sum_i \sum_w y_{1,f,wheat,i,w,s} + \sum_i \sum_w y_{1,f,barley,i,w,s} \leq 1 \qquad \forall \text{ f,s} \quad (31)$$

$$\sum_{i} x_{2,f,sugbt,i,s} + \sum_{i}\sum_{w} y_{1,f,sugbt,i,w,s} + H6_{f,sugbt} \qquad (32)$$

$$+H5_{f,sugbt} + H4_{f,sugbt} \leq 1 \qquad \forall \text{ f,s}$$

$$\sum_{i} x_{2,f,onion,i,s} + \sum_{i}\sum_{w} y_{1,f,onion,i,w,s} + H6_{f,onion} + H5_{f,onion} \qquad (33)$$

$$+H4_{f,onion} + H3_{f,onion} \leq 1 \qquad \forall \text{ f,s}$$

$$\sum_{i} x_{2,f,potato,i,s} + \sum_{i}\sum_{w} y_{1,f,potato,i,w,s} + H6_{f,potato} + H5_{f,potato} \qquad (34)$$

$$+H4_{f,potato} + H3_{f,potato} \leq 1 \qquad \forall \text{ f,s}$$

$$\sum_{f}\sum_{i} x_{2,f,potato,i,s} \leq PotatoContract \qquad \forall \text{ s} \qquad (35)$$

$$\sum_{i} x_{2,f,alf2,i,s} = \sum_{i}\sum_{w} y_{1,f,alf1,i,w,s} \qquad \forall \text{ f,s} \qquad (36)$$

$$\sum_{i} x_{2,f,alf3,i,s} = \sum_{i}\sum_{w} y_{1,f,alf2,i,w,s} \qquad \forall \text{ f,s} \qquad (37)$$

$$\sum_{i} x_{2,f,alf4,i,s} = \sum_{i}\sum_{w} y_{1,f,alf3,i,w,s} \qquad \forall \text{ f,s} \qquad (38)$$

$$\sum_{c}\sum_{i} x_{2,f,c,i,s} + open_{f,2,s} = 1 \qquad \forall \text{ f,s} \qquad (39)$$

$$\sum_{w} y_{2,f,fall,i,w,s} \leq x_{2,f,fall,i,s} \qquad \forall \text{ f,fall,i,s} \qquad (40)$$

$$\sum_{w} y_{2,f,alf2,i,w,s} = x_{2,f,alf2,i,s} \qquad \forall \text{ f,i,s} \qquad (41)$$

$$\sum_{w} y_{2,f,alf3,i,w,s} = x_{2,f,alf3,i,s} \qquad \forall \text{ f,i,s} \qquad (42)$$

$$\sum_{w} y_{2,f,alf4,i,w,s} = x_{2,f,alf4,i,s} \qquad \forall \text{ f,i,s} \qquad (43)$$

$$\sum_{i}\sum_{w} y_{2,f,gcorn,i,w,s} + \sum_{i}\sum_{w} y_{1,f,gcorn,i,w,s} + \sum_{i}\sum_{w} y_{1,f,scorn,i,w,s} \qquad (44)$$

$$+H6_{f,gcorn} + H6_{f,scorn} \leq 2 \qquad \forall \text{ f,s}$$

$$\sum_{i}\sum_{w} y_{2,f,scorn,i,w,s} + \sum_{i}\sum_{w} y_{1,f,gcorn,i,w,s} + \sum_{i}\sum_{w} y_{1,f,scorn,i,w,s} \qquad (45)$$

$$+H6_{f,gcorn} + H6_{f,scorn} \leq 2 \qquad \forall \text{ f,s}$$

$$\sum_{i}\sum_{w} y_{2,f,barley,i,w,s} + \sum_{i}\sum_{w} y_{1,f,barley,i,w,s} \qquad (46)$$

$$+\sum_{i}\sum_{w} y_{1,f,wheat,i,w,s} \leq 1 \qquad \forall \text{ f,s}$$

$$\sum_{c}\sum_{i}\sum_{w} y_{2,f,c,i,w,s} = 1 \qquad \forall \text{ f,s, with} \qquad (47)$$

t = a crop year within the 6-year planning horizon, with possible values of 1 through 6, or within the 6-year period following the planning horizon, with possible values of 7 through 12.

f = the field in which the cropping activity takes place {F1,…, F10}.

c = the crop {onion, potato, sugar beet, wheat, barley, grain corn, silage corn, alfalfa (1st through 4th year), fallow, and open}

i = the irrigation technology {furrow, reuse furrow, solid set, wheel line, center pivot, drip}

w = the deficit irrigation level {0.0, 0.5, 0.6, 0.7, 0.8, 0.9, 1.0}

ρ_s = probability of the 6-year water supply scenario s

r = interest rate on operating loans and savings

d = discount rate

FAC = number of acres per field (fields assumed to be equal size)

p_c = price received per unit of crop c

$yld_{c,i,w}$ = yield per acre of crop c, under irrigation technology i, and deficit irrigation level w

$j_{c,i}$ = cost of spring planting per acre of crop c, under irrigation technology i.

h_c = cost of fall preparation or planting per acre of crop c

fxdcost = fixed cost per acre of land owned, such as a water district fee per acre and land taxes

$maxyld_{c,i}$ = maximum yield for crop c, under irrigation technology i, given no water deficit

ky_c = yield response coefficient for crop c, which reflects sensitivity to water stress

$ETmax_c$ = gross water requirement of crop c over the growing season to achieve maximum yield

Ppt = precipitation received during the growing season, which reduces irrigation requirements

IrrigEffic = the proportion of water delivered to the field that reaches the crop root zone

Water = per acre water allotment for the growing season

TotAcres = total number of acres available for cropping activities

$RRate_{onion}$ = rental rate of an acre eligible for onions (i.e. an acre not planted to onions in previous 5 years)

$RRate_{other}$ = rental rate of an acre not eligible for onions

$EligOnion_{t,s}$ = acres eligible to be rented for onions in period t of scenario s

$EligAlf_{t,i,s}$ = acres of alfalfa with productive lifespan remaining in years 7 through 9 for scenario s; acres inherit the irrigation technology used in year 6

$EligOther_{t,s}$ = acres eligible to be rented for crops other than onions in period t of scenario s; a function of $EligOnion_{t,s}$ and $EligAlf_{t,i,s}$.

$NetRv_{alf,i,d1}$ = net revenue from alfalfa under irrigation technology i, assuming no deficit irrigation (w =d1)

$H1_{f,c}$ = the crop c to which field f was planted six years prior to the first year of the planning horizon (i.e. planted in the first year of the previous (historical) planning horizon) (=0 if not planted, or 1 if planted)

$H2_{f,c}$ = the crop c to which field f was planted five years prior to the first year of the planning horizon (=0 if not planted, or 1 if planted)

$H3_{f,c}$ = the crop c to which field f was planted four years prior to the first year of the planning horizon (=0 if not planted, or 1 if planted)

$H4_{f,c}$ = the crop c to which field f was planted three years prior to the first year of the planning horizon (=0 if not planted, or 1 if planted)

$H5_{f,c}$ = the crop c to which field f was planted two years prior to the first year of the planning horizon (=0 if not planted, or 1 if planted)

$H6_{f,c}$ = the crop c to which field f was planted one year prior to the first year of the planning horizon (=0 if not planted, or 1 if planted)

PotatoContract = a fixed acreage of potatoes (expressed as number of fields) contracted in advance with local processors

$open_{f,t}$ = field f is left unprepared and unplanted in the fall of year t (=0 if not left open, or 1 if left open). This contrasts to “fallow,” which indicates that a field is either abandoned (if prepared or planted in the previous fall), or not planted in the spring (if left open in the previous fall).

The producer's objective (equation 6) is to maximize the expected discounted stream of profit from the 6-year planning horizon through the selection of fall and spring crop activities (*x* and *y*, respectively). Decisions made in "crop year" t consist of fall decisions ($x_{t,f,c,i,s}$) and spring decisions ($y_{t,f,c,i,w,s}$). Crops that are either fall-planted or require fall bed-preparation require the following fall decisions: 1) number of fields to plant or prepare, and 2) an associated irrigation technology, i, for each field. Spring decisions for each crop, c, include the following: 1) number of fields to keep (if c is a fall-planted crop) or number of fields to plant (if c is spring-planted), 2) an irrigation technology, i, for each field (note: for some crops, decisions made in the preceding fall impose an irrigation technology on the spring decision), and 3) a deficit irrigation level, w, for each field. The optimal choice of *x* and *y* depends on past, current, and potential future water supplies, denoted by s.

Economic profit for a particular crop year of the planning horizon, given water supply scenario, s, is described in (7). Crop mix, output price, number of acres planted, yield per acre, and cost of spring and fall activities partly determine profit. Fixed costs (which include land taxes and a water district charge), and the opportunity cost of money and time also influence profit. A 7% interest rate (r) is charged for short-term operating loans (Stanger, 2005: personal communication). The opportunity cost of investing equity funds in the farm is also assumed to be 7%. It has been argued that the rate charged for equity funds should be less than the rate charged for borrowed funds, because the commercial lending rate includes fees that are not relevant to equity funds (American Agricultural Economics Association Task Force, 1998: 33). However, it is difficult to accommodate a separate interest rate for each source of funds in this model. Time preferences are captured with a 5% discount rate (d). This rate strikes a balance between a conservative discount rate of 3% (the average real return on a risk-free asset (American Agricultural Economics Association Task Force, 1998: p33)), and a higher discount rate (7%) that is based on the assumed interest rate. The effect of choosing a lower versus higher discount rate on the model's solution is discussed in Peck (2007).

FAC, a constant that represents the size of each field and appears first in the profit calculation, is necessary when *x* and *y* are binary variables. For example, $\sum_{f} y_{1,f,c,i,w,s1}$ calculates the number of fields planted to crop c under irrigation technology i and deficit irrigation level w in the spring of year 1 for water scenario s1. This integer has to be multiplied by the acres per field (FAC) before profit is calculated, because the revenue and cost data are per acre, not per field.

Yield for crop c, under irrigation technology i and deficit irrigation level w, is calculated in equation 8, which is a linear yield response function popularized by Doorenbos and Kassam (1979). Water is assumed to be the only limiting input to crop yield. The degree to which actual crop yield ($yld_{c,i,w}$) deviates from maximum yield ($maxyld_{c,i}$) in a particular year is a function of the crop's sensitivity to water stress (indicated by the empirically-based coefficient ky_c), precipitation received during the growing season (Ppt), and the proportion (w) of the crop's maximum irrigation water requirement ($ETmax_c$-Ppt) actually provided. This formulation of the yield response function assumes water deficits occur at an equal proportion across the entire growing season. It is preferable to model strategic deficit irrigation, in which crops are deficit irrigated during their least-sensitive growth stages. Data are insufficient, unfortunately, to model this approach. The season-long deficit approach likely overestimates yield losses associated with a particular deficit level. Thus the model is likely to choose deficit irrigation as an optimal strategy less frequently than a model that assumes strategic deficit irrigation.

Terminal values are introduced in the model via equation 9. Terminal values are needed to capture the following two sources of future profit: 1) alfalfa planted or maintained in year 6 that has productive value in years 7 through 9, and 2) the rental value of land in years 7 through 12. Decisions made in years 1 through 6 impact the flow of profit from years 7 through 12; equation 9 is an attempt to incorporate this dynamic relationship into the decision problem.

Equations 10 through 45 are the detailed representation of the general constraints presented in equations 2 through 5. Equation 10 constrains the sum of water use across all fields, accounting for the application efficiency of various irrigation technologies, to no more than the farm's total water allotment. Total water allotted equals the per acre water allotment (set by the irrigation district) multiplied by total acres owned or leased. This equation must be met in every year of every water supply scenario.

Equations 11 and 12 prevent crop-irrigation-deficit combinations that are not observed in the area from entering the solution. Cost and yield data are not available for combinations not observed in the area, so they are not included in the model. The GAMS language uses set notation to reduce the volume of required code. A by-product of this notation, however, is that cropping activities not currently practiced in the area are created through the set notation. Suppose, for example, that set c = {onions, corn} and set i = {drip, center pivot}. Set notation allows the modeler to specify one equation that applies to every (c, i) combination, rather than specifying one equation for each combination. Suppose, however, that not all (c, i) combinations occur in the study area; for example, (corn, drip) does not occur in the Vale Oregon Irrigation District. Equations 11 and 12 prevent this combination from entering the solution. Equation 13 states that cropping activities can take on binary values only. That is, a cropping activity can either be implemented in a particular field (i.e. take on the value 1), or not implemented (i.e. take on the value 0). This is in contrast to a continuous definition of cropping activities, in which the activity variable could take on any continuous value representing the number of acres on which the activity is implemented.

Equations 14 through 21 constrain the scope of specific crop activities in the fall of year 1 to reflect agronomic rules that prevent pests and diseases. These rules, derived from conversations with producers, represent agronomic guidelines that they adhere to quite rigidly. It is beyond the scope of this study to test the economic optimality of these rules. Biological response functions that capture pest and disease dynamics are not readily available, and are therefore not directly included in the economic decision model. These functions are captured through crop rotation constraints instead.

Interpretation of a few equations will help elucidate the nature of the agronomic constraints. Equation 14 prevents the planting of small grains (wheat and barley) on the same acreage in two consecutive years. It specifically states that field f can be planted to wheat in year 1 if it was not planted to wheat or barley in year 6 of the historic period (i.e. H6). The historic period consists of the six years that immediately precede the current planning horizon; historic crop activities are exogenous to the decision model. Equation 14 states, algebraically, that the sum of the listed activities (each of which can take the value of 0 or 1) cannot exceed 1. Equations 15 through 17 are the equivalent to (14) for other crops. Note that sugar beets, onions, and potatoes require four to five years between plantings to avoid pests and diseases. These agronomic practices create inter-year dynamics.

Equation 18 states, for year 1, that the number of fields allocated to potatoes cannot exceed the "PotatoContract," regardless of the water scenario. Potatoes in the study area are grown exclusively under contract with local processors, so producers are constrained to the quantity that the processor requests. A relatively small portion of onions and sugar beets are also grown under contract. It was decided, however, to exclude this option from the model. Equations 19 through 21 require the producer to maintain alfalfa that is one or more years old through its fourth year of production. The producer does, however, have an opportunity to abandon newly planted alfalfa in its first spring. Alfalfa is used in crop rotations to enhance soil quality; equations 19 through 21 ensure that alfalfa is left in place sufficiently long to accomplish this. Equation 22 forces the producer to make a fall decision for each field in year 1; they can choose to prepare, plant, or leave each field open.

Equations 23 through 29 constrain spring crop activities in year 1. Equation 23 limits the spring acreage of each fall-planted or prepared crop to no more than the number of fields planted or prepared in the preceding fall. Winter wheat acreage, for example, is planted exclusively in the fall; therefore, wheat acreage cannot be increased in the spring. Onion acreage, which is prepared in the fall, cannot typically be increased in the spring due to adverse field conditions. Equation 23 therefore generates intra-year dynamics. Equations 24 through 26 simply transfer fall alfalfa acreage to spring alfalfa acreage, thus preventing the abandonment of alfalfa stands that are one or more years old.

Equation 27 states that corn (grain or silage) cannot be planted in the same field more than two consecutive years. Algebraically, field f can be planted to grain corn in year 1 if it was planted to grain or silage corn in year H6 but not year H5, or if it was planted to corn in year H5 but not year H6. Equation 28 presents the same constraint for silage corn. Equation 30 must accompany equations 27 and 28 for them to perform correctly. It states that each field can be planted in the spring to only one crop-irrigation-deficit combination; fallowing is included in the list of spring crops. Equations 27 and 28 each sum over several corn-irrigation-deficit combinations for year 1, and the sums are allowed to equal 2; thus, without equation 30, one field could be planted to two different combinations in the same year. Equation 29 expresses the agronomic constraint for spring-planted barley. The equations explained above are defined for year 1 only. Equations 31 through 47 essentially repeat this block for year 2. Blocks for years 3, 4, 5, and 6 are similar in content, and therefore not presented here. To avoid the influence of a subjective crop history, the farm's ten fields (35 acres per field) are assumed, in this study, to have no recent crop history.

Care must be taken in constructing the above constraints, due to the stochastic water supply. First, all constraints must be met in every water supply scenario. The water constraint in equation 10, for example, must be met in the event of a full or dry spring. Additionally, constraints must be constructed to properly account for past water supply conditions. The number of fields planted to onions in year 4 of water scenario [Full Dry Full Full ___ ___], for example, cannot exceed the number of fields that remain eligible for onions, which is determined by cropping activities during the three preceding years, i.e. activities in scenario [Full Dry Full ___ ___ ___]. Use of the subscripts s1 through s6 ensures that current activities are constrained by their respective water supply histories.