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# Sequential Stochastic Production Decisions for a Perennial Crop: The Yield/Quality Tradeoff for Alfalfa Hay

**Steven C. Blank, Steve B. Orloff, and Daniel H. Putnam**

The "optimal cutting schedule" for alfalfa hay is described as a function of the tradeoff between rising yield and falling quality of alfalfa over time and the local market prices being offered for different qualities of hay during the harvest season. Field test results quantify the yield/quality tradeoff for a California case study. A general decision rule is then derived to assist growers in making cutting decisions during a season. Finally, the optimal cutting schedule is shown to be the sum of sequential decisions for cuttings throughout the harvest season, with no schedule being best a priori.

*Key words:* alfalfa, cutting schedule, decision rule, yield/quality tradeoff

## Introduction

Alfalfa hay is a perennial crop widely produced across the United States because it is an important part of livestock feeding programs (Freeze and Hironaka; Grisley, Stefanou, and Dickerson; Konyar and Knapp 1986, 1990; Ward). As a perennial, alfalfa is a continuously produced, occasionally harvested crop. This means a farmer's inventory of alfalfa continues to expand over time as an optimal production process is followed (Marble), and inventory is periodically converted into hay when harvest methods (Orloff and Marble 1997a) are used to create a marketable product. Therefore, alfalfa hay growers face sequential production decisions that, in sum, make up what is often referred to as the "optimal cutting schedule."

The optimal cutting schedule for alfalfa hay has long been an issue drawing much attention from growers and researchers alike (e.g., Cothern; Klonsky and Marble; Marble). The reason for this attention is that the cutting schedule affects the quality and quantity of alfalfa harvested (Marble; Orloff and Marble 1997b) which, in turn, affects the total revenues and profits received by a grower (Klonsky and Marble). Specifically, there is a tradeoff between yield and quality of alfalfa; higher quality comes at the cost of lower yields and vice versa. In general, a shorter interval between cuttings results in higher quality forage, but a lower yield per acre from the cutting. Market prices are higher for

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Steven C. Blank is an extension economist in the Agricultural and Resource Economics Department, the University of California, Davis, and a member of the Giannini Research Foundation; Steve B. Orloff is a University of California farm advisor in Siskiyou County; and Daniel H. Putnam is an extension agronomist in the Agronomy and Range Science Department, the University of California, Davis.

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high-quality alfalfa hay than for lower quality product (Grisley, Stefanou, and Dickerson; Ward), but exact price levels are determined by market factors such as the relative supply of and demand for each quality of hay (Konyar and Knapp 1990). Thus, prices and yields appear to be inversely related in the aggregate market, but both of those factors are stochastic in a grower's decision analysis. Consequently, individual growers are unable to identify an "optimal" cutting schedule. Currently, most growers choose an arbitrary cutting schedule, based on their preferences and prior experience, before the harvest season begins. They adhere to this schedule during the season without much regard to production or market factors (Orloff and Marble 1997a). Such an inflexible strategy is unlikely to result in optimal profit levels for individual growers.

This problem has received virtually no attention from economists because it straddles agronomic and economic issues. The agronomic issues involve the tradeoff between yield and quality of alfalfa and the factors influencing that relationship. The agronomic literature has long dealt separately with factors influencing yield and those influencing quality (e.g., Marble). In recent years, some attention has been directed at the yield/quality tradeoff (e.g., Orloff and Marble 1997a,b). However, the economic issues have received little direct attention because they are inaccessible without the assistance of an agronomist.

In an economic sense, the issue is how to maximize a grower's wealth, not alfalfa yield or quality attributes. Thus, production and marketing issues both must be addressed in the decision process. Market factors, especially prices, cannot be considered until the final product attributes have been determined. And, as noted above, alfalfa hay attributes are essentially a function of the yield/quality tradeoff which cannot be specified without agronomic expertise.

As a result, the existing economic literature focusing on optimal management strategies for alfalfa hay in particular, and perennial crops in general, has rarely dealt with the sequential production decisions faced by growers within a single season. Analyses by Klonsky and Marble, and Debertin and Pagoulatos represent two of a very few attempts to address those decisions for alfalfa. Instead, the literature offers numerous analyses of related questions using annual decision periods.

Debertin and Pagoulatos examined the impacts of three alternative management strategies for alfalfa production within a whole-farm plan. They arbitrarily broke the production season into fixed periods to facilitate a linear programming model involving alfalfa and alternative cropping options. The problems of tractability faced in such an analysis probably explain why most other economic studies of alfalfa have dealt with decisions made across years (e.g., Ward et al.). Although supply response models for alfalfa have been developed (e.g., Knapp; Knapp and Konyar), annual data were used despite the economists' knowledge of factors affecting yields within a year. For example, Knapp (p. 100) states, "alfalfa yields depend on a variety of factors including location, variety, age of the stand, level of variable inputs, climatic factors, and the number and timing of cuttings"; yet the analysis is restricted such that "alfalfa yields are a function only of the stand age."

Another topic in the recent economic literature dealing with alfalfa is its role in crop rotations. Maynard, Harper, and Hoffman employed stochastic dominance methods to analyze five crop rotations using experimental yield data from Pennsylvania. Also, Foltz et al. used simulation and budget analysis to rank 72 alternative midwestern cropping systems. In these studies, like most others, assumptions were made regarding annual alfalfa yields and prices. In fact, it is common for economic studies of perennial crop production to utilize analytical tools and/or theories which assume producers' price expectations are based on perfect foresight (Knapp).

This article addresses the difficulties of dealing with sequential production decisions within a season by presenting the results of a research project undertaken in a sequential manner. The objective is to link the agronomic and economic issues affecting an alfalfa grower's ability to maximize his or her wealth. The issues are linked both theoretically and empirically by development of a decision rule designed to be used by individual growers for identifying the optimal cutting schedule at each point in time during a harvest season.

The remainder of the article proceeds as follows. First, the demand for hay is explained briefly. Changes in hay demand motivated this project. Second, field research results which quantify the yield/quality tradeoff are reported for a region in California. These results serve as an empirical case study. Third, the agronomic decision is converted to an economic decision using a theoretical model that helps identify relevant variables for deriving a simple decision rule. The decision rule is then applied sequentially with the field research results in the empirical case study. Finally, some implications and conclusions are drawn from the analysis.

## Demand for Hay

Forage quality is an important factor in the market for alfalfa hay because the demand for hay comes primarily from two general groups, dairy producers and all other users (Grisley, Stefanou, and Dickenson; Konyar and Knapp 1986; Ward), and each group's willingness to buy hay is influenced by quality factors. Specifically, dairy producers want highly digestible "dairy-quality" hay and are willing to pay extra for it. Because other hay users do not need the same quality hay, they are unwilling to pay premium prices.[1] Thus, hay prices can be viewed as coming primarily from these two market segments (Blake and Clevenger; Blank and Ayer; Cothern). Hay producers therefore need to be mindful of the hay quality needs of dairymen and attentive to prices from the two major market segments when making decisions about when to cut alfalfa during the year.

Alfalfa hay is an integral component of the feed ration for milking cows and cannot be easily replaced by other feeds. The forage quality or digestibility of alfalfa hay in the dairy ration directly affects the milk output of the cow. Hence, highly digestible alfalfa is strongly sought after by the dairy industry in California, particularly for top-producing cows. For marketing purposes, the forage quality of alfalfa is expressed in terms of total digestible nutrients (TDN). While 54% TDN was once sufficient, dairy producers now seek 54.5%, 55%, or even 56% TDN alfalfa hay (TDN is computed on a 90% dry matter basis). Alfalfa hay with a TDN of 54.5% to 56% is considered to be "premium" grade, according to U.S. Department of Agriculture (USDA) standards (see USDA/Agricultural Marketing Service, p. 4). Hay with lower TDN levels is considered lower quality.

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[1] Horse owners do have quality considerations. Their parameters are more visual and physical (i.e., weeds, mold, dust). Horse owners do pay extra for "quality hay," but usually not as much as for premium dairy hay. Also, the horse market segment is small compared to the dairy segment; thus it is lumped into the nondairy segment in this analysis, along with beef producers and producers of other classes of livestock.

**Table 1. Alfalfa Hay Prices in Northern California**

| Year | Price by Quality Grade (nominal $/ton) | | | Premium vs. Fair Differential (%) |
|---|---|---|---|---|
| | Premium | Good | Fair | |
| 1990 | 109.55 | 99.52 | 83.84 | 30.7 |
| 1991 | 99.03 | 89.69 | 70.75 | 40.0 |
| 1992 | 89.62 | 74.99 | 59.60 | 50.4 |
| 1993 | 103.07 | 93.94 | 70.58 | 46.0 |
| 1994 | 112.80 | 101.25 | 85.46 | 32.0 |
| 1995 | 109.30 | 100.94 | 83.82 | 30.4 |
| 1996 | 118.81 | 108.63 | 95.47 | 24.5 |
| 1997 | 129.79 | 111.11 | 95.70 | 35.6 |
| 1998 | 127.34 | 106.40 | 84.77 | 50.2 |
| 1999 | 106.43 | 87.89 | 63.29 | 68.2 |
| Average | 110.57 | 97.44 | 79.33 | 39.4 |

Notes: Source for prices, USDA/Agricultural Marketing Service. Differentials were computed by the authors.

There are five quality designations for alfalfa hay now recognized by the USDA. Only the premium, good, and fair quality designations are used in this analysis because those are the segments from which hay producers must choose most often when making the yield versus quality tradeoff decision described here. Although market factors move the range of prices up and down, there are always discrete jumps between prices of each quality grade. Dairy-quality (premium grade) hay receives a significantly higher price than does fair quality hay, as shown in table 1. Therefore, because prices depend on quality, if the tradeoff between expected yield and quality exists, then hay growers face a tradeoff between yield and price.

## The Yield/Quality Tradeoff

The research reported below shows alfalfa yield and quality are inversely related, suggesting that harvesting alfalfa at an immature growth stage will result in high forage quality but low yield. Conversely, delaying cutting until a more mature growth stage will result in higher yield but poorer, often unacceptable, forage quality. This relationship takes on even greater importance with the current standards used for dairy-quality hay. The yield reduction associated with producing such high-quality hay can be severe. The first step in evaluating this tradeoff is to define the degree to which harvest date affects yield and forage quality. Knowledge of this relationship can serve as the basis for harvest timing decisions.

### *Field Research on the Yield/Quality Tradeoff for Particular Cuttings*

A series of field trials were conducted to quantify the relationship for a particular cutting between irrigated alfalfa's growth stage at harvest and the expected yield and forage quality. Field studies were conducted in two high-mountain valleys of northeastern California using two alfalfa varieties deemed suitable for the climate of the region.

Alfalfa was harvested every two to three days throughout normal first and second cutting periods. A completely randomized design with four replications was used. The first harvest was made at the late vegetative pre-bud stage; the last harvest was made at full bloom. The total number of harvests per cutting period averaged 12, ranging from 9 to 14 depending on the cutting and the location. First cut developed more slowly and had more harvest dates than did second cutting. Forage yield was evaluated at each harvest date, and each plot was subsampled to determine the moisture content and forage quality. Acid detergent fiber (ADF), which measures the indigestible fiber in the plant, was evaluated using near infrared spectroscopy analysis (Orloff and Marble 1997b). TDN is calculated from the ADF value. The field trial study was conducted in 1996, and repeated in 1997.

### *Cutting Yield and Quality Results*

An estimate of plant maturity is a far more accurate method for timing harvests than the use of calendar date. This choice was particularly apparent in the field trials discussed here, because the spring of 1996 was unseasonably cool and alfalfa development was delayed approximately 10–14 days compared with 1997.

As alfalfa matured from the late vegetative pre-bud stage to full bloom, the daily increase in yield per acre for the first cutting was 80 pounds averaged over two years, two varieties, and two locations (figure 1). In other words, each day delay in first-cutting harvest resulted in an 80-pound increase in yield. The rate of yield increase was greater for second cutting; each day delay resulted in an increase of 112 pounds (figure 1).

These two general forecasts of change in yield per day come from a linear regression model estimated using the 712 data points illustrated in figure 1.[2] The regression equation is specified as

$$(1) \qquad Y_{x,t} = \underset{(0.013)}{2.163} + \underset{(0.001)}{0.04\Delta} - \underset{(0.020)}{0.0442X} + \underset{(0.002)}{0.016\Delta X}$$
$$R^2 = 0.76,$$

where $Y_{x,t}$ is the yield for cutting number $x$ at time $t$ expressed in days; $\Delta$ is the day during the 37-day harvest window when the alfalfa is cut (scaled from $-18$ to 18, with the middle point between these values being the typical harvest date); $X$ is a dummy variable (0 for the first cutting, 1 for the second cutting); $\Delta X$ is $\Delta$ times $X$; and the standard errors of coefficients are in parentheses. The two graph lines in figure 1 represent the yield estimates derived from equation (1) for first and second cuttings made at each day within the harvest window.

As expected, forage quality declined as the alfalfa matured. On first cutting, the ADF content increased 0.33% per day. This equates to a loss of 0.22% of TDN (calculated from the ADF value) per day (figure 2). Forage quality declined at an even more rapid rate on second cutting. The ADF content increased 0.4% per day on second cutting. This increase in ADF equates to a 0.27% loss in TDN per day delay in second cutting.

To forecast expected change in quality per day, a linear regression estimate of ADF was developed from the 712 data points illustrated in figure 2, and it was used to calculate TDN:

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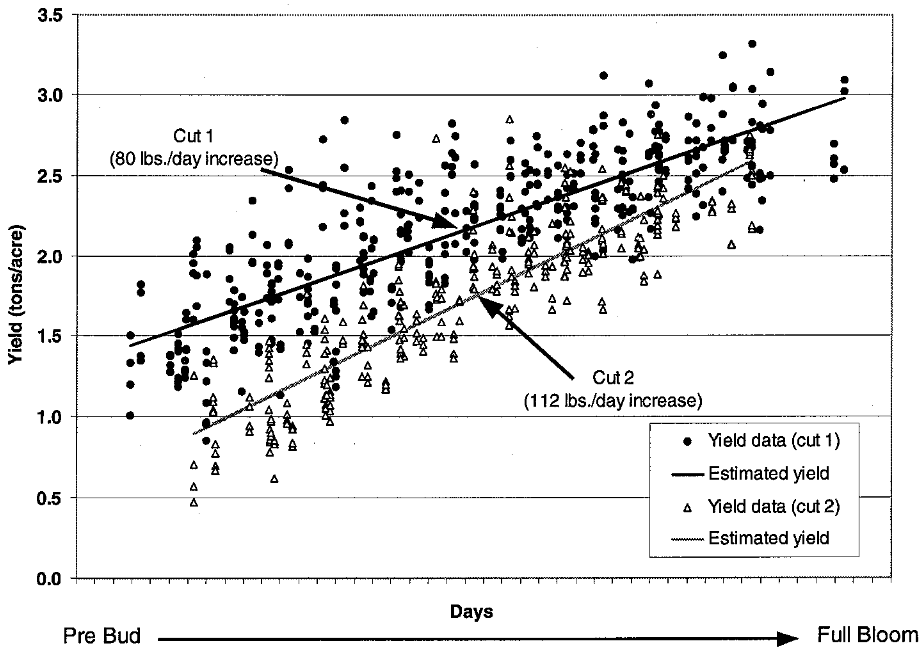
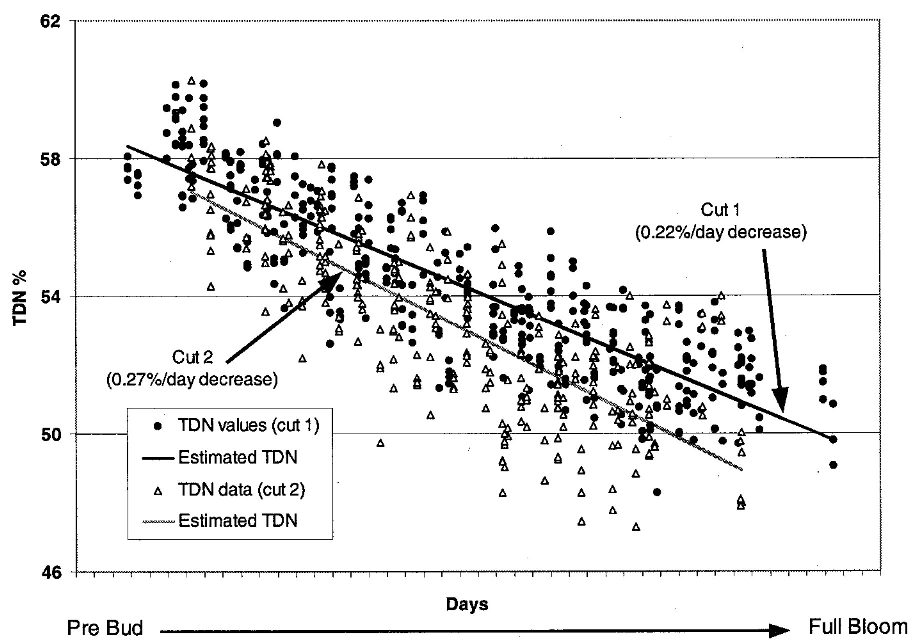
[2] Several linear and nonlinear specifications were estimated for both equations (1) and (2), and the reported linear models performed best with the data.




Note: Each tick mark on the X-axis represents one day in the 37-day harvest window.

**Figure 1. Daily change in the yield of alfalfa harvested from pre-bud to full bloom for 1st and 2nd cuttings (averaged over two locations, two years, and two varieties)**




Note: Each tick mark on the X-axis represents one day in the 37-day harvest window.

**Figure 2. Daily change in total digestible nutrient (TDN) content of alfalfa harvested from pre-bud to full bloom for 1st and 2nd cuttings (averaged over two locations, two years, and two varieties)**

(2)
$$ADF_{x,t} = \underset{(0.102)}{29.295} + \underset{(0.010)}{0.327\Delta} + \underset{(0.158)}{1.831X} + \underset{(0.018)}{0.069\Delta X}$$
$$R^2 = 0.73,$$

(3)
$$TDN_{x,t} = 0.9(82.38 - [0.7515 ADF_{x,t}]).$$

Numbers in parentheses in equation (2) are the standard errors of coefficients. The two graph lines appearing in figure 2 are the estimated TDN levels derived from equation (3) (Orloff and Marble 1997b) for first and second cuttings made at each day within the harvest window.

### *Harvest Strategy Research*

The timing of an individual cutting clearly influences the amount of growing time available for subsequent alfalfa cuttings. Therefore, to analyze different strategies for cutting management, it is necessary to consider the entire production season rather than just an individual cutting. Given the restricted growing season in the California intermountain area, growers typically must decide between three or four cuttings, with three being most common. Not only is the total number of cuttings per season important, but the actual timing of each cutting is important.

An additional study was conducted over three years at the Intermountain Research and Extension Center in Tulelake, California, to compare different strategies for cutting management. The trial consisted of three cutting schedules with six alfalfa varieties. A randomized complete block design with four replications was used. Three cutting schedules were evaluated, two 3-cut schedules and one 4-cut schedule, to represent common practices for cutting management. The two 3-cut schedules had identical first and third cutting dates; only the date of the second cutting was varied. For one of the 3-cut schedules, the second cutting was early (approximately 35 days after the first) in an attempt to produce dairy-quality alfalfa on second cutting. The date of the second cutting was later for the other 3-cut schedule, approximately 45 days after the first cut. The 4-cut schedule was cut earlier in spring and later in fall than the 3-cut schedules. The interval between cuttings with the 4-cut schedule was typically 32 days, the time period necessary to fit four cuttings into the restricted growing season. Forage yield was determined at each harvest, and subsamples were taken for forage quality evaluation. Data were collected in 1994, 1996, and 1997.

### *Harvest Strategy Results*

Analysis of variance results indicated highly significant effects on both yield and forage quality for year, alfalfa variety, cutting schedule, and the interactions of year by cutting schedule and cutting schedule by variety. The 3-cut schedules yielded significantly more total output per year than did the 4-cut schedule (table 2). The 4-cut schedule typically yielded about 0.75 tons less than the best 3-cut schedule each year. Averaged over the three years, the 3-cut schedule with a delayed second cut was the highest yielding treatment.

While the 3-cut schedules clearly resulted in higher alfalfa production per year, the forage quality data were very different. The forage quality of alfalfa receiving the 4-cut schedule was superior (higher TDN value) to that of either 3-cut schedule for all cuttings

**Table 2. The Effect of Three Different Cutting Management Strategies on Alfalfa Yield and Total Digestible Nutrient (TDN) Level (averaged over three years)**

| | Cutting | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | 1st Cut | | 2nd Cut | | 3rd Cut | | 4th Cut | |
| Cutting Schedule | Tons/ Acre | TDN | Tons/ Acre | TDN | Tons/ Acre | TDN | Tons/ Acre | TDN |
| 3-Cut (early 2nd) | 2.84 | 52.7 | 2.15 | 51.3 | 1.87 | 52.2 | | |
| 3-Cut (delayed 2nd) | 2.82 | 52.8 | 2.43 | 49.9 | 1.83 | 52.9 | | |
| 4-Cut | 2.08 | 54.3 | 1.55 | 53.9 | 1.45 | 54.6 | 1.11 | 58.1 |

(table 2). All four cuttings of the 4-cut schedule were above or close to dairy-quality alfalfa, while none of the cuttings for the 3-cut schedules resulted in dairy-quality alfalfa. As expected, the early second cutting 3-cut schedule resulted in higher forage quality for second cutting than did the delayed second cutting. However, the 3-cut schedule with a delayed second cutting resulted in improved forage quality for the third cutting.

In summary, the field research results show (*a*) both yield and quality change over time, and (*b*) the seemingly deterministic relationships among yield, quality, and time include significant uncertainty. Some variance is attributable to deterministic factors such as farm location, alfalfa variety, and the cutting schedule being used. However, once deterministic factors are accounted for, significant variance remains due to the numerous factors beyond a farmer's control, such as climate, nutrient stock carryover between periods, and incidence of pests and disease. This explains why the spread of observations is so wide at each point in time in figures 1 and 2.

To convert the quality/yield results into terms useful in dealing with the economic decision facing growers, the quality/price relationship first must be considered, and then the yield/price relationship. To begin, the quality/price relationship is stochastic because so many of the market factors affecting price received by a grower are beyond the grower's control. As shown in table 1, price levels and price relationships between hay quality grades can change dramatically from year to year. Prices can also be volatile within a single year (Cothern; Konyar and Knapp 1986). The perceived yield/price relationship is actually a compilation of the relationships between yield and time, time and quality, and quality and price. Given the uncertain nature of the subrelationships, it is reasonable to describe the indirect yield/price relationship as stochastic. The sequential production decisions facing a grower involve significant risk.

## Dynamic Decisions Under Risk

"In agricultural economics, most studies of dynamic decisions under risk have been empirical.... Ito stochastic control is a tool for constructing the theory to complement these empirical results" (Hertzler, p. 1126). Ito control simplifies the stochastic structure of the model and finds optimality conditions using a stochastic calculus. Such a model provides a useful theoretical structure for analyzing the case of alfalfa hay producers because it allows expected utility to be maximized over time subject to multiple and correlated risks. Thus, a stochastic control model is outlined briefly below to show the theoretical origin of the empirical decision rule derived. (For a full discussion of Ito stochastic control models and their derivation, interested readers should see Hertzler.)

### *A Theoretical Model of Hay Harvest Decisions*

Hertzler writes, "Like deterministic optimal control, Ito control maximizes an objective function subject to differential equations for the state variables" (p. 1129). Wealth is a state variable common to all farmers. In this study, the objective of a risk-averse alfalfa farmer is assumed to be the maximization of his or her expected utility subject to the farmer's stochastic change in wealth:

(4)
$$J(W_o) = \underset{q,\psi}{\text{Max}}\, E\left\{\int_0^T e^{-\rho_t}U(q)\,dt + e^{-\rho_T}V(W_T) \,\middle|\, W_o = w_o\right\},$$

subject to:

(5)
$$dW = \left[\delta_w W + (\delta_a - \delta_w)p_a A - p_a g(A, \psi) + \pi - p_q q\right]dt + p_a A\sigma_a dz_a - p_a s_a(A, \psi)dZ_a + d\pi,$$

where $U$ and $V$ are direct utility of the farmer's consumption and terminal wealth; $J$ is indirect utility of wealth; $W$ is wealth which can be invested off-farm at the risk-free rate $\delta_w$; $q$ is the farmer's consumption at price $p_q$; $\psi$ is a vector of control variables; $\rho$ is the farmer's rate of time preference at current time $t$, or over the planning horizon $T$; $A$ is the farmer's alfalfa inventory [which is a function of product attributes, $A = f(Y, Q)$] valued at price $p_a$ and expected to receive premium $\delta_a - \delta_w$ above the risk-free rate; yield ($Y$) is a function of optimal production inputs and their total costs and a time transformation, $Y = f_y(C, \tau)$; $C$ is the sum of costs for a vector of $i$ optimal production inputs applied over the entire year [$C = \Sigma(c_1, c_2, ..., c_i)$]; hay quality is a negative function of a time transformation, $Q = -f_q(\tau)$, where a time transformation is some physical change that occurs in the product as time passes; $g$ is the physical rate of degradation of the farmer's alfalfa inventory; $\pi$ is the revenue from production above variable costs, or gross margin; $\sigma_a$ and $s_a$ are standard deviations of returns to alfalfa and of physical degradation; $dz_a$ and $dZ_a$ are Weiner processes; and $d\pi$ is the stochastic change in the gross margin.

The stochastic change in wealth, equation (5), reflects the risks faced by an alfalfa grower. Maximizing expected utility subject to this single equation is equivalent to maximizing expected utility subject to multiple equations for wealth, alfalfa inventory (yield and quality), and prices. The term $(\delta_a - \delta_w)p_a A$ is the value added to purchased inputs from the grower's efforts. Price and yield risk appear in the term $p_a A\sigma_a dz_a$—price directly, and yield through the function $A = f(Y, Q)$ which states that a farmer's inventory per acre is derived from yield and hay quality. Degradation in the inventory's value due to declining quality over time is the term $p_a g(A)$. Degradation is risky because of the term $p_a s_a dZ_a$. Gross margin ($\pi$) is specified below.

As a continuously produced perennial crop, it is important to remember a farmer's alfalfa inventory has an expected "book value" of $p_a A$ which is converted to a cash value only when it is harvested and marketed. At that time, the farmer receives sales revenue ($R$) on a per acre basis equaling price per ton ($P$) times yield ($Y$). In this model, $\pi$ is the portion of revenue represented by gross profit, adding to wealth. In the case of a single cutting decision,

(6)
$$\pi \equiv P(Q[-\tau], M)Y(\tau, C) - C - h - K,$$

where price is a function of hay quality and market factors, $P = f_p(Q, M)$; $M$ reflects the price effects from market factors; $h$ is the cost per acre of all harvesting operations; and $K$ is the sum of a vector of $j$ fixed costs. Thus, gross margin is stochastic because of price and yield, which are both functions of a time transformation ($\tau$), which is the primary control variable.

Based on the theoretical model above, in essence, identifying the optimal cutting schedule for alfalfa hay involves choosing between different combinations of prices and yields available over time. First, there is the choice of the *timing* of each cutting, given the knowledge that delaying a cutting increases the yield but at the expense of receiving a lower price per ton because of lower forage quality. Second is the choice of *how many* cuttings will be made during a single year. The first choice affects the second; i.e., choosing longer time periods between cuttings may reduce the total number of cuttings that can be made in one season. Thus, the optimal solution requires focusing on both the yield/quality tradeoff and the tradeoff between market prices from different market (quality) segments. The theoretical model facilitates reaching this conclusion by enabling us to identify the time transformation as the control variable.

### *Choosing the Time to Cut*

From the model above [equation (6)], a simplified decision rule can be developed to show that choosing the best time to cut alfalfa involves identifying when the available yield and price result in the highest possible revenue per acre. At any given time, the market for alfalfa hay offers a price versus yield tradeoff. At relatively low yield levels, growers would receive a high price per ton because the alfalfa would be of high (dairy) quality. However, if a grower delays cutting until the quality falls below premium (dairy) quality, a significantly lower price will be offered. At that point, a slight increase in yield is insufficient to compensate for the large drop (discrete jump) in price. A significant yield increase is needed to compensate for the price drop from premium to good or from good to fair quality hay. In other words, growers face a tradeoff between a high price/low yield combination versus a low price/high yield combination.

Identifying which of the two relevant price/yield combinations will generate the highest revenue must be done when the forage quality, as measured by TDN value, is 54.5 or higher. Obviously, delaying the cutting decision until after forage quality falls below the 54.5 TDN level eliminates the option of producing dairy-quality hay and receiving the high market price. Thus, it is at the time when quality is at the 58–54.5 TDN level that a producer must forecast the likely outcomes for the two market options: cut for quality now or cut later for yield.

The decision rule is based on the concept of breakeven (Dillon) between the two time options (time 1 or time 2) for a single cutting (cutting $x$), occurring when the profits ($\pi$) from each cutting option are equal ($\pi_{x,1} = \pi_{x,2}$). This is possible because, as defined in equation (6), total production and fixed costs for the season ($C, K$) are not affected by the harvest schedule, and harvest costs for a single cutting ($h$) are the same whenever the cutting occurs; thus all three variables are irrelevant to the timing decision.[3]

[3] This is true when a grower hires a custom harvester who charges a flat rate per acre, which is often the case (Blank et al.). As is shown later in this analysis, a fixed rate per acre is needed as an incentive to harvesters to gain the higher quality/lower yield hay for dairies. If custom harvesters are paid on a fixed rate per ton, their incentive is to cut only high-yield alfalfa (Marcum and Blank), causing the grower to receive lower quality hay, and thus lower prices per ton. If growers harvest hay with their own equipment, harvest costs are slightly higher when yields are higher.

Total production costs per year (e.g., total irrigation costs, chemical costs, etc.) are not affected by when cuttings are made. Also, harvest costs per cutting are not affected by the number of cuttings per year. So, the breakeven point is defined as follows:

$$E(R_{x,1}) = E(R_{x,2}), \quad (7)$$

where $E(R_{x,t})$ is a grower's expected revenue for cutting $x$ at time $t$. Here, $t$ is limited to two time options: time 1 is when yield is as high as possible while still generating dairy (premium) quality hay, and time 2 is when yield has expanded further to exactly offset the lower price that will be received for the lower quality hay. Equation (7) can be restated in terms of price and yield:

$$P_{x,1} \cdot E(Y_{x,1}) = E(P_{x,2} Y_{x,2}), \quad (8)$$

where revenue available currently (at time 1) is a known price which is immediately available times an expected yield, and revenue expected at time 2 is the product of an expected price and expected yield. Also, the price expected at time 2 is conditional on the quality at time 2, which is a function of expected yield. Thus, equation (8) can be manipulated to give the relationship between prices and yields at the breakeven point:

$$\frac{P_{x,1}}{E(P_{x,2} \mid Y_{x,2})} = \frac{E(Y_{x,2})}{E(Y_{x,1})}, \quad (9)$$

$$\text{s.t.: } P_{x,1} > E(P_{x,2}) \text{ and } E(Y_{x,2}) > E(Y_{x,1}).$$

Equation (9) shows that revenues received at two points in time will be equal if the ratio between the two prices is equal to the ratio between the two yields. The constraints assure normal conditions exist where yields increase over time, causing some discrete price decrease. The equation can be expressed as differentials in prices and yields, as reported in table 1, by subtracting one from each side of the equality. Then, to account for the uncertainty of price and yield at time 2, the equation must be expressed as an inequality, and a risk premium ($\varphi$) can be added to the left side (Ahlbrecht and Weber) to reflect the utility-maximizing decision rule for risk-averse farmers.[4] After these modifications, the decision rule becomes to cut now (at time 1) for quality if

$$\frac{P_{x,1} - E(P_{x,2})}{E(P_{x,2} \mid Y_{x,2})} + \varphi \geq \frac{E(Y_{x,2} - Y_{x,1})}{E(Y_{x,1})}, \quad (10a)$$

or to cut later (at time 2) for yield if

$$\frac{P_{x,1} - E(P_{x,2})}{E(P_{x,2} \mid Y_{x,2})} + \varphi < \frac{E(Y_{x,2} - Y_{x,1})}{E(Y_{x,1})}. \quad (10b)$$

Such a decision rule can be used each time the sequential decision arises (Burt).

An example will illustrate how the decision rule in equations (10a) and (10b) can be applied. First, a hay grower in the intermountain area of northern California is at

[4] For a risk-neutral farmer, $\varphi = 0$, but the inequality is used to reflect the fact that cash flows received at time 2 are discounted relative to cash flows received at time 1. For a risk-averse farmer, $\varphi > 0$.

time 1: his hay tests at 54.5 TDN—the lowest level to receive the dairy-quality price. If this is the grower's first cutting, he expects a yield of approximately 2.12 tons per acre, according to equations (1)–(3). Assuming the local hay market is offering the average prices listed in table 1, the grower knows he can get \$110.57 per ton for dairy (premium) quality hay, but only if he cuts immediately. Further delaying the cutting risks having the hay quality fall below the 54.5 TDN level, and will result in a lower price.[5] Thus, the grower must choose at that point in time either to cut for quality and capture the premium price ($P_{1,1}$ = \$110.57) with an expected yield, $E(Y_{1,1})$, of 2.12 tons, or to wait until the yield increases enough to at least offset the lower price that will be received.

To calculate the higher yield needed at time 2 to offset the lower expected price, the grower substitutes the current price for premium hay into equation (10) as $P_{1,1}$, and the current price for fair quality hay as $E(P_{1,2})$. Assuming the market is again offering the average price in table 1, $E(P_{1,2})$ is \$79.33. Calculating the left-hand side of equation (10) with these prices gives a price differential of 39.4% (ignoring $\varphi$). This means to offset the 39.4% drop in expected price at time 2, the yield differential (increase) must be at least 39.4% of the current available yield. Thus, yield expected at time 2 must be at least 2.96 tons/acre to generate the same total revenue (assuming the price for fair quality hay does not change) available at the present (time 1). From the results in figure 1 and equation (1), a yield of 2.96 for the first cutting is not often available. Using the highest expected yield normally available in figure 1 results in the price differential being greater than the yield differential, making equation (10a) the relevant decision rule. Consequently, the grower is better off to cut immediately for quality.

For the second cutting in the example above, the same process would be used to find the relevant decision rule. The grower would expect to get above 54.5 TDN quality hay (at time 1) with a yield of 1.78 tons per acre. Assuming the same two prices were available for premium and fair quality hay, the differential would again be 39.4% (and again assuming no risk premium, $\varphi$). This would require the grower to obtain a yield of at least 2.48 tons at time 2. Figure 1 and equation (1) show that such a yield on a second cutting does occur within the range of a reasonable cutting interval, so the grower could cut for yield any day after the required yield was realized, and the resulting expected revenue would be higher than revenue received if the grower cut for quality. In other words, the numbers would make equation (10b) the correct decision rule.

The decision rule in equations (10a) and (10b) can be used when comparing any two possible cutting times. Although the examples above focus on the most common cutting times, when alfalfa tests as premium or fair quality, the same approach can be used earlier or later in the production process. In particular, growers sometimes will cut their alfalfa very early to get TDN levels of 56% to 58% because some price premiums are received. However, the markets for "supreme" quality hay (which is superior to premium quality hay) and "low" quality hay (which is the lowest of the five quality designations used by the USDA) are both thin, and few sales are made. Nevertheless, growers thinking of cutting early to capture the very high-quality hay prices available still face the price/yield tradeoff. Few sales of supreme quality hay are observed in California markets because the price premiums received are rarely sufficient to compensate for the lower yields received at that early point in the production process.

[5] A risk-averse grower (for whom $\varphi > 0$) will not want to risk such a revenue shortfall. Thus, in contrast to a risk-neutral grower, the risk-averse producer would cut earlier when emphasizing quality, and later when emphasizing yield.

**Table 3. Yield Differentials Between Various Alfalfa Qualities**

| | Yield Differential (%) | | | |
|---|---|---|---|---|
| Cut | Supreme to Premium | Premium to Good | Good to Fair | Premium to Fair |
| 1st Cut | 19.01 | 17.97 | 16.93 | 37.94 |
| 2nd Cut | 30.65 | 23.46 | 21.72 | 50.27 |

Note: The quality grades and their respective TDN levels are as follows: Supreme, >56; Premium, 54.5–56; Good, 52–54.5; and Fair, <52.

To illustrate this circumstance, the price differentials and prices needed to break even when cutting alfalfa with higher TDN levels were calculated using the yield differentials derived from the northern California field test results reported earlier. Assuming 54.5 to 56 TDN hay was receiving the $111/ton average premium price from table 1, the following expected differentials and prices, respectively, would be needed: for supreme quality (57 TDN) hay on the first cutting, -19% and $132; and for second-cutting supreme quality hay, -30.7% and $145. Based on these values, it is highly unlikely that cutting alfalfa with 56–58 TDN levels is as profitable as cutting 54.5–56 TDN alfalfa (forage with the usual TDN range to receive dairy-quality prices) in the intermountain area of northern California. Table 3 presents a summary of the yield differentials calculated from the field research reported earlier. Thus, to justify cutting for the higher quality, the relevant price differential would have to exceed the yield differential reported in the table.

As shown in table 1, the northern California hay price differentials for individual years during the 1990s ranged from 24.5% to 68.2%, revealing that the decision reached by a grower could be to cut for quality (when the differential is higher) or to cut for yield (when the differential is lower). No single strategy was always best. This point is illustrated by evaluating the 1996 and 1998 years. Those years fell within the period over which the field tests were conducted and represent extremes in the price differentials made available by the market during the 1990s (as shown in table 1). In 1996, for example, the price differential (discrete price jump) between quality grades is small (only 24.5% between premium and fair), so using the decision rule to compare premium versus good, and good versus fair quality hay leads to cutting for yield (fair quality) on both the first and second cuttings. In contrast, in 1998, the wide price differentials lead to cutting for quality on both cuttings (although the second cutting may be for good, rather than premium quality hay).

### *Choosing the Number of Cuttings*

Choosing the optimal number of cuttings per year should be a sequential process involving repeated use of the decision rule above to calculate which cutting schedule maximizes a grower's total profits per acre from all cuttings in a year. In practice, however, individual growers often use the same cutting strategy every year. In the northern intermountain area of California, climatic limitations have translated into growers cutting either three or four times per year throughout the life of the stand, which is normally three or four years. Thus, traditional cutting strategies have evolved with no assessment of the performance of these strategies relative to the potential optimal profits. To find that optimum, the decision facing hay growers in the intermountain region is how to achieve the objective of maximizing annual profits per acre ($\pi$):

$$\pi \equiv R - C - H - K, \tag{11}$$

where

$$R = \sum_{x=1}^{N} (P_x Y_x) \quad \text{and} \quad H = h \cdot N,$$

$$\text{s.t.: } N = 3 \text{ or } 4.$$

Note that equation (11) is a restatement of equation (6), and thus the theoretical model directs and justifies the choices made in the empirical work. In this model of the intermountain areas in California, annual gross profits per acre ($\pi$) are defined to equal the sum of revenues minus costs from each cutting, where the number of cuttings per year ($N$) is limited by climate/season length to be either three or four. Costs relevant to this decision include only those operating expenses per acre incurred by a grower during the harvesting process ($H$). Because other costs of production, fixed ($K$) or variable ($C$), do not vary in total between a 3- or 4-cut schedule, they do not affect the outcome and are not relevant to this analysis. The focus therefore shifts from gross profits to "harvest profits," defined as equaling revenues minus total harvest costs ($R - H$).

To identify the best cutting schedule in this case, the production data in equations (1)–(3) and the 1990–99 price data in table 1 were used to create a stochastic Monte Carlo simulation model of profits per acre for various cutting schedules observed in the field. Harvest costs per cutting ($h$) were estimated to be \$31 per acre based on the survey data reported in Long et al. This figure represents the cost per acre charged by custom harvesters to perform all harvesting functions.[6] To account for the fact that hay prices cannot be perfectly forecast, the simulation model ran 1,000 trials with premium and fair hay prices drawn from triangular distributions created using the lowest price, highest price, and average price from the 1990–99 data in table 1 for each quality grade. Also, stochastic yields were defined to be normally distributed around the mean empirical results reported for each cutting in this study. This procedure was followed for 10 separate cutting schedules as a case study. The simulation's average results are reported in table 4.

Two conclusions can be reached from the empirical results in table 4. First, this analysis clearly shows that a cutting schedule focusing only on cutting for quality or only on cutting for yield is not the best strategy for hay growers in the northern areas of California. Mixed cutting schedules (derived from sequential decisions) outperformed schedules with a single focus. For example, schedule D in table 4 is a 3-cut strategy which includes a first cut for yield followed by a second cut for yield and a third cut for quality (denoted by Y,Y,Q). Schedule D outperformed schedule B, which includes three cuts for yield (Y,Y,Y). Schedule D had higher profits than did schedule B in 64% of the trials in the simulation, with average profits of about \$10 per acre more than the all-yield cutting strategy. A mixed 4-cutting schedule (Y,Y,Q,Q), as shown by schedule I,

[6] Blank et al. found there is little difference between custom rates per acre and the per acre costs of owning and operating alfalfa harvesting equipment in California for average-scale growers.

**Table 4. Estimated Results for Various Alfalfa Cutting Schedules**

| Schedule | Cut for: [a] | Average Annual Revenue ($/acre) | Average Annual Harvest Profits ($/acre) |
|---|---|---|---|
| A | Q,Q,Q | 519 | 426 |
| B | Y,Y,Y | 529 | 436 |
| C | Q,Y,Y | 527 | 434 |
| D | Y,Y,Q | 539 | 446 |
| E | Q,Y,Q | 537 | 444 |
| F | Q,Q,Q,Q | 613 | 489 |
| G | Q,Y,Q,Q | 631 | 507 |
| H | Q,Y,Y,Q | 622 | 498 |
| I | Y,Y,Q,Q | 633 | 509 |
| J | Q,Y,Y,Y | 617 | 493 |

Note: Harvest profits are defined here to be revenues minus harvest costs; no production costs have been included in the analysis.

[a] Q indicates the alfalfa was cut for quality; Y means the hay was cut for yield. For example: Schedule C includes three cuts (Q,Y,Y), the first for quality and the second and third for yield.

also outperformed a 4-cut strategy focusing only on quality (Q,Q,Q,Q in schedule F). Profits from schedule I were about $20 per acre higher on average than those from schedule F.

The second conclusion drawn from table 4 is that a mixed 4-cutting schedule is likely to be the most profitable strategy for hay growers in this region, if climate allows four cuttings within a season. Schedule I, the most-profitable 4-cut schedule, was, on average, about $63 per acre more profitable than schedule D, the most-profitable 3-cut schedule, and outperformed it in 94% of the trials.

When compared to the results for the field tests reported in table 2, these simulation results reinforce the importance of using an estimate of plant maturity and the decision rule in equation (10), rather than calendar dates to time harvests. The field tests were harvested using typical calendar-based cutting schedules and, as a result, generated less than optimal revenues and harvest profits. For example, in the 4-cut schedule, the field results show the first two cuttings were made a bit too late to get premium quality hay, thus foregoing the opportunity to receive the desired higher price.

One final issue arising when comparing 3-cut versus 4-cut schedules is the timing of cash flows. Assuming revenues are received immediately after each cutting, a 4-cut schedule will result in cash flows being received at earlier dates than for a 3-cut schedule. Expressing cash flows in present-value terms creates “compensatory gains” (Burt) for schedules placing cash into a grower’s hands earlier. In this case, compensatory gains from 4-cut schedules are opportunity costs to 3-cut schedules. However, the compensatory gains of faster cash flows from 4-cut schedules are likely to be insignificant (a few days interest) and, following Burt’s suggestion, can be interpreted as part of the random variation in cash flows.

## Implications and Conclusions

In this study, a theoretical model of the sequential stochastic production decisions facing perennial crop producers guides the development of a simple decision rule which is applied in an empirical case study of alfalfa hay. Our results lead to at least two conclusions.

First, it is noted that the most profitable 3-cut (Y,Y,Q) and 4-cut (Y,Y,Q,Q) schedules in table 4 are identical for the first three cuttings (Y,Y,Q), as are the second most profitable schedules of each type (Q,Y,Q and Q,Y,Q,Q). Based on this observation, by using the decision rule sequentially during a season, a grower does not need to choose between a 3-cut or 4-cut schedule a priori; climate conditions will determine whether or not a fourth cutting is profitable each year. This is a significant conclusion because there is evidence showing some growers do, in fact, make the 3- versus 4-cut scheduling decision based on historical patterns and calendar dates rather than on current conditions. The two most profitable 3-cut schedules identified in the simulation analysis (table 4) are the schedules most often used by growers at present.[7] This finding implies that if those growers had considered the option (climate permitting), they would have found a fourth cutting was profitable.

The second general conclusion drawn from this study is that market prices signal the optimal sequence of production decisions for an individual grower. The decision rule derived here shows how much additional yield is needed to offset the expected price drop being signaled by price relationships between quality grades. By reacting to the market price differentials, a grower can make informed production decisions more likely to lead to an optimal outcome at the time of each cutting and over an entire season. In other words, a grower does not have to decide a priori whether to pursue a particular quality of hay.

The results of this study are relevant to alfalfa growers anywhere, as well as to producers of other perennial crops. Anytime a crop is continuously produced and occasionally harvested, the farmer faces sequential production decisions like those evaluated here. For any perennial crop (e.g., tree and vine crops), the decision of when to harvest involves the tradeoff between increasing quantity and (after some date) decreasing quality (i.e., perishability increases). Maximizing profits requires mastering the tradeoff.

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## References

Ahlbrecht, M., and M. Weber. "An Empirical Study on Intertemporal Decision Making Under Risk." *Manage. Sci.* 43,6(1997):813–26.

Blake, M., and T. Clevenger. "A Linked Annual and Monthly Model for Forecasting Alfalfa Hay Prices." *West. J. Agr. Econ.* 9(1984):195–99.

Blank, S., and H. Ayer. "Government Policy Cross-Effects: The Cotton and Dairy Programs' Influence on Alfalfa Hay Markets." *Agribus.: An Internat. J.* 3(1987):385–92.

Blank, S., K. Klonsky, K. Norris, and S. Orloff. "Acquiring Alfalfa Hay Harvest Equipment: A Financial Analysis of Alternatives." Pub. No. 92-1, Giannini Foundation Information Series, University of California, Davis, December 1992.

[7] This observation was made by one of the authors while conducting the field tests. In most cases, the growers have used the same cutting schedule each year for some period of years. Also, most growers keep to a historic norm of a three- or four-year stand life.

Burt, O. R. "Decision Rules for the Dynamic Animal Feeding Problem." *Amer. J. Agr. Econ.* 75(1993): 190–202.

Cothern, J. H. "Processing, Transporting, and Pricing California Alfalfa Hay." Leaflet No. 2890, Div. of Agr. Sci., University of California, Davis, June 1977.

Debertin, D., and A. Pagoulatos. "Optimal Management Strategies for Alfalfa Production Within a Total Farm Plan." *S. J. Agr. Econ.* 17(1985):127–37.

Dillon, C. R. "Advanced Breakeven Analysis of Agricultural Enterprise Budgets." *Agr. Econ.* 9(1993): 127–43.

Foltz, J., J. Lee, M. Martin, and P. Preckel. "Multiattribute Assessment of Alternative Cropping Systems." *Amer. J. Agr. Econ.* 77(1995):408–20.

Freeze, B., and R. Hironaka. "Effect of Form of Hay and Carcass Quality on the Economics of Concentrate: Hay Substitution in Cattle Feedlot Diets." *West. J. Agr. Econ.* 15(1990):163–74.

Grisley, W., S. Stefanou, and T. Dickerson. "Factors Affecting the Price of Hay at a Pennsylvania Auction." *Northeast. J. Agr. and Resour. Econ.* 14(1985):48–56.

Hertzler, G. "Dynamic Decisions Under Risk: Applications of Ito Stochastic Control in Agriculture." *Amer. J. Agr. Econ.* 73(1991):1126–37.

Klonsky, K., and V. Marble. "The Optimal Cutting Schedule for Hay." In *Proceedings of the 1988 Alfalfa Symposium*, pp. 23–31. Kansas City MO: The Alfalfa Council, February 1988.

Knapp, K. C. "Dynamic Equilibrium in Markets for Perennial Crops." *Amer. J. Agr. Econ.* 69(1987): 97–105.

Knapp, K., and K. Konyar. "Perennial Crop Supply Response: A Kalman Filter Approach." *Amer. J. Agr. Econ.* 73(1991):841–49.

Konyar, K., and K. Knapp. "Demand for Alfalfa Hay in California." Res. Rep. No. 333, Giannini Foundation, University of California, Riverside, May 1986.

———. "Dynamic Regional Analysis of the California Alfalfa Market with Government Policy Impacts." *West. J. Agr. Econ.* 15(1990):22–32.

Long, R., B. Reed, K. Klonsky, K. Brittan, and P. Livingston. "Sample Costs to Establish an Alfalfa Stand and Produce Alfalfa Hay: Sacramento Valley, Flood Irrigated." Coop. Ext. Ser., University of California, Davis, 1998.

Marble, V. L. "Optimizing Alfalfa Production in Desert Areas of the Southwestern United States." In *Proceedings of California Alfalfa Symposium*, pp. 75–91. Fresno CA: The Alfalfa Council, 1973.

Marcum, D., and S. Blank. "Custom Harvest of Alfalfa Hay in Northeastern California: Use a Fixed Price or Commit to a Percentage?" Coop. Ext. Serv., University of California, Davis, February 1999.

Maynard, L., J. Harper, and L. Hoffman. "Impact of Risk Preferences on Crop Rotation Choice." *Agr. and Resour. Econ. Rev.* 26(1997):106–14.

Orloff, S., and V. Marble. "Harvest Management." In *Intermountain Alfalfa Management*, eds., S. B. Orloff and H. L. Carlson, pp. 104–07. Pub. No. 3366, Div. of Agr. and Nat. Resour., University of California, Oakland, 1997a.

———. "Quality and Quality Testing." In *Intermountain Alfalfa Management*, eds., S. B. Orloff and H. L. Carlson, pp. 117–19. Pub. No. 3366, Div. of Agr. and Nat. Resour., University of California, Oakland, 1997b.

U.S. Department of Agriculture, Agricultural Marketing Service. "Alfalfa Hay: California Market Summary." *Livestock and Grain Market News.* USDA/AMS, Washington DC, 1998.

Ward, C. E. "Buyer Preferences for Alfalfa Hay Attributes." *N. Cent. J. Agr. Econ.* 9(1987):289–96.

Ward, C., A. Dowdy, R. Berberet, and J. Stritzke. "Economic Analysis of Alfalfa Integrated Management Practices." *S. J. Agr. Econ.* 22(1990):109–15.