Ranching, Invasive Annual Grasses, and the External Costs of Wildfire in the Great Basin: A Stochastic Dynamic Programming Approach

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Abstract

The spread of invasive annual grasses and resulting escalation of wildfire frequency and severity pose a significant and growing threat to the economic and ecological viability of the rangelands in the Great Basin. While private ranchers have the option to limit the severity of wildfires through fuels removal treatments, few ranchers engage in such land treatments. Without internalizing the public cost of wildfire suppression in the decision problem, private ranchers likely to under-invest in fuels treatments. In this article, using a bio-economic model of rancher decision making, we analyze the private incentives for engaging in land treatments. We find that the downside shocks on available grazing land due to wildfires are proportionately smaller for larger ranches and that for that reason larger ranches exhibit a greater ability to adjust production in response to wildfires, thus implying a potential source of increasing returns to scale in ranch operation in presence of wildfire risks. We also find that valuation of fuels treatment is substantially different between a private rancher and a "social planner" that internalizes wildfire suppression costs in the decision problem.

Introduction

The spread of invasive annual grasses poses a significant and growing threat to the economic and ecological viability of the vast area of natural rangelands in the Great Basin. Recent studies have estimated that over half the sagebrush biome that occupies 100 million acres of western high desert, including most of the Great Basin, has already been invaded by non-native annual grasses such as cheatgrass and medusahead (Miller and Tausch 2001). It is estimated that cheatgrass alone is now the dominant species on over 25 million acres of rangeland (BLM 2000), and the trend is further escalating. In many circumstances it is either impossible or prohibitively expensive to reverse the conversion of rangeland to invasive annuals (Stringham, Krueger, and Shaver 2003; Bestelmeyer et al. 2009). The potential for irreversible ecological change increases the urgency of the problem of invasive annual grasses in the Great Basin.

These invasive grasses influences the economic and ecological services provided by Great Basin rangelands, the majority of which is owned and managed by public agencies, with a large proportion privately ranched through grazing leases. Invasive annuals lower the productivity of rangeland for cattle grazing, reducing rancher profits and the long-run viability of ranching; reduce the ability of rangeland to support native wildlife and plants, including threatened species such as the Sage Grouse; and decrease the value of rangeland for hunters and other recreational users. Perhaps the most problematic and pervasive consequences of these ecological changes, however, is the increase in the frequency and severity of rangeland wildfires, which in turn promotes further spread of invasive annuals (Whisenant 1990; Miller and Tausch 2001; Pellant, Abbey, and Karl 2004; Chambers et al. 2007).

Options are available for land management to slow down the trend. These options include 1) pre-fire fuels removal treatments such as herbicide application, mechanical brush removal,

targeted livestock grazing, and prescribed burning, and 2) post-fire restoration treatments such as reseeding with vegetation to compete with invasive plants. Pre-fire treatments prevent large fires that are costly to suppress and that make the land more vulnerable to invasive grasses. Pre-fire treatments are proactive, less expensive, and have higher success rates than post-fire rangeland rehabilitation and restoration (Humphrey and Schupp 2004). However, the benefits of fuels removal treatments are less well documented and analyzed than restoration treatments (Grote 1999), and current public lands policies tend to focus on post-fire rehabilitation (Hemstrom et al. 2002; Forbis et al. 2006).

Private ranchers are appear to have incentives to proactively control invasive weeds and fuel loads on the rangelands they use because rangeland wildfires impose direct costs on ranchers through damage to ranch infrastructure and by making rangeland temporarily unavailable for grazing. However, the observation is that few ranchers engage in such land treatments. High transactions costs involved in obtaining permits necessary to implement such treatments on public lands are a possible institutional constraint that precludes private efforts. Cost of treatment is another likely private disincentive. Furthermore, layers of externalities associated with rangeland use and wildfires also likely explain low private incentives. For example, wildfires generate external costs to society such as the harm to human health by releasing smoke and particulate matter, the release of carbon sequestered in rangeland soils and plants, and the cost of fire suppression, which is borne almost entirely by federal, state, and local governments. Ranchers operating on western rangelands, however, do not bear these external costs of wildfires and therefore are likely to under-invest in fuels treatments.

In this article we analyze the private incentives for engaging in rangeland treatments that would contribute to the slowing down of the on-going ecological change in the Great Basin and

to the reduction of societal cost including fire suppression costs. In particular, we consider how wildfire influences rancher production and fuels treatment decisions and how these decisions, in turn, influence the external costs of wildfire in terms of fire suppression cost. To analyze these issues we present a bio-economic model of rancher decision making and solve it numerically using a stochastic dynamic programming (SDP) solution technique. The model, building on the framework developed in Kobayashi and Rollins (2009), is parameterized to characterize rangeland ecological conditions, probabilistic wildfire, fuel accumulation dynamics, and the features of cow-calf operations that are typical in the Great Basin.

We use the SDP model to examine four questions. First, we examine how ranchers adjust their production (e.g. herd size and composition) in response to wildfires, and how these adjustments are influenced by rangeland ecological condition. We consider the Sagebrush Steppe ecosystem in the lower-elevation Great Basin, where the rangeland vegetation is changing from the historic plant community characterized by a mix of sagebrush and native perennial grasses (which we refer in this article as state 1) to a plant community dominated by overgrown sagebrush (state 2) or by invasive annual grasses (state 3).

Second, we examine whether and how a rancher's production decisions in the presence of wildfire risk is related to ranch size in terms of total acreage of rangeland available for grazing. The most direct cost of wildfire to a rancher is from the loss of grazing land for a period after a wildfire[1] and the way in which grazing land availability constrains cattle production likely depends on ranch size. We consider three ranch sizes in this article: a small ranch of 1,500 acres, a medium-sized ranch of 5,000 acres, and an aggregate ranch of 240,000 acres. The aggregate ranch captures decision making under the assumption that the herd and landscape is managed by

a single decision maker. The aggregate ranch is used in the analysis to approximate the production and rangeland management decisions of a benevolent social planner.

The third question we consider is how rangeland state and ranch size influence a rancher's incentives to engage in preemptive wildfire fuel removal treatments. While treatment reduces the risk of future wildfires, it reduces rangeland acreage available for cattle production in the current period. In particular, the analysis provides an insight into why ranchers in the Sagebrush Steppe rarely voluntarily pursue fuels treatments at current costs.

The fourth and final question we consider is the potential inefficiency resulting from the externality of wildfire suppression costs to private rancher objective. To address this question, we analyze how total acres burned and total herd-size optimal solutions on the 240,000-acre representative ranch would change if the wildfire suppression costs were internalized in their decision making.

We find that the downside shocks on available grazing land due to wildfires are proportionately smaller for larger ranches and that larger ranches exhibit a greater ability to adjust production in response to wildfires, thus implying a potential source of increasing returns to scale in ranch operation in presence of wildfire risks. We also find that valuation of fuels treatment is substantially different between a private rancher and a "social planner." As a result, private incentives for implementing fuels treatment is higher for more productive rangeland states, while the opposite result is obtained when wildfire suppression costs are internalized into the decision problem.

Previous Literature

The primary methodological contribution of this article is incorporation in the SDP model of the interaction between rangeland state, wildfire, and cattle herd dynamics. Explicit modeling of this

interaction allows us to analyze how a cow-calf producer adjusts production in anticipation of and in response to stochastic wildfire events, and how these adjustments determine the costs of wildfires to the rancher, the external costs of wildfire to society, and the rancher's incentive to engage in preemptive fuels removal treatments. Previous studies have used SDP models to analyze optimal stocking rate decisions and optimal timing of land management treatments to balance current ranch profits and future range productivity (Burt 1971; Pope and McBryde 1984; Karp and Pope 1984; Bernardo 1989). In contrast to these studies, we model future forage availability as a consequence of current fuels treatment through reduced fire size in the future. Thus, we analyze the trade-off between current fuels treatments, which temporarily remove grazing land from production, and future fuel accumulation, which determines wildfire size and cost. In addition, other studies such as Hu, Ready, and Pagoulatos (1997), Janssen et al. (2004), and Finnoff et al. (2008) have used dynamic economic models to consider the short- and long-run ecological impacts of livestock grazing. These studies, however, do not consider the influence of wildfire on rancher decision making, which is of great importance in rangeland ecosystems such as the Sagebrush Steppe of the Great Basin.

Several studies have examined the relationship between rangeland management and wildfire. Eiswerth and van Kooten (2002) and Epanchin-Niell, Englin, and Nalle (2009) analyze the tradeoff between preemptive fuels removal treatments and post-wildfire restoration using discrete-state Markov-chain models. Livestock grazing is not considered in these two studies, however, so the interaction between fuels treatment decisions and cattle herd dynamics is not addressed. Huffaker and Cooper (1995) study ranching in an ecosystem system similar to the one we study, focusing on how plant succession dynamics between native perennials and invasive annual grasses determine short-run and long-run rangeland ecological health. Huffaker

and Cooper (1995), however, include wildfire as an exogenous factor that the rancher cannot influence through fuels removal treatment or any other rangeland management strategy. Janssen et al. (2004) incorporate fire as an endogenous factor in their model of rangeland management; however, wildfire is included only as a land treatment strategy that has a perfectly predictable and beneficial outcome. In contrast to these works, we model rangeland wildfires as a random event that imposes costs on both ranchers and public agencies responsible for wildfire suppression, and we consider a setting where the damage from wildfire is endogenized through decisions about preemptive action.

Previous economic studies of interactions between livestock grazing and long-run rangeland health do so in the context of stocker operations (e.g. Torell et al. 1991; Huffaker and Cooper 1995; Hu et al. 1997; Janssen et al. 2004; Finnoff et al. 2008). With many Great Basin ranchers being cow-calf operators, the capital asset nature of cattle (Jarvis 1974) may plays an important role in understanding rancher incentives and thus for designing appropriate policies for range management. Relative to stocker operations, herd size adjustments are more difficult for cow-calf operations because herd-size expansion occurs through the slow process of biological reproduction or through finding breeding stock with desirable genetic traits. We examine in this article how this "stickiness" in production due to the dynamics of reproduction in a cow-calf operation affects optimal herd-management and rancher incentives to undertake fuels removal treatments.

Model Specification and Numerical Implementation

Building on the technique presented in Kobayashi et al. (2007), we develop a continuous-state, discrete-time SDP model for a cow-calf producer operating in the presence of wildfire risks. The rancher is assumed to maximize the expected net present value of his enterprise on a fixed area

of rangeland, where each year cattle are reproduced, raised, and sold. Cow and heifer stocks are treated as state variables, with biological reproduction and growth processes constituting their equations of motion. The third state variable is fuels or dead vegetation, which accumulates over time and determines wildfire size and the associated damages given a wildfire event. We model the number of fires on a ranch in a given year as a stochastic event whose distribution is known to the rancher and depends on both ranch size and rangeland ecological condition. We consider two opportunity costs from wildfire in the model: (i) burned areas unavailable for grazing in the season following the fire and (ii) wildfire suppression costs. Fuel stock is assumed to determine fire size but does not influence the probability of a fire event. Accordingly we assume that fuels accumulation can be controlled by the rancher through fuels removal treatments, but that the rancher cannot influence the number of wildfire events on their ranch. Because pre-fire fuel treatment is more successful when cattle are also restricted from grazing for a season, the model assumes that rangeland receiving fuels treatments cannot be grazed in the year treatment is implemented.

We assume the following sequence of events within a year. A model year starts in late summer, when wildfires are most likely to occur. We allow for, if necessary, "emergency" herd-size adjustment after fires in order to satisfy the grazing land availability constraint in the spring grazing season. Emergency herd-size adjustments are disadvantageous for the rancher, it forces them to sell their cattle at a heavily discounted price. In winter, cattle are fed with supplements; deaths also occur in winter. Next, in winter through early spring, the decision maker makes the land treatment decision. In spring, calving occurs and the grazing season starts; brood cows may be purchased at this time. Breeding occurs during the grazing season. Finally, decisions about calf and cull-cow sales occur at the end of each period before the next wildfire season.

In this article, we consider four different decision-maker scenarios (Table 1). We consider the decision problem of a 1,500-acre individual cow-calf rancher (scenario (a)), a 5,000-acre individual rancher (scenario (b)), 240,000-acre "aggregate rancher" (scenario (c)), and 240,000-acre "social planner" (scenario (d)). The aggregate ranch captures decision making under the assumption that the herd and landscape is managed by a single decision maker. The social planner is an extension of aggregate rancher scenario where the decision maker internalizes the cost of wildfire suppression.

Cattle Herd Dynamics

Herd dynamics are captured using two state variables: cows (COW_t) and heifers (HEF_t). Births of female and male calves ($FCALF_t$ and $MCALF_t$, respectively) are specified as:

(1) $$FCALF_t = MCALF_t = 0.5\beta(1-\delta)(COW_t - ADJ_t^{COW}),$$

where ADJ_t^{COW} denotes post-fire cow-stock adjustment. We use β=0.8075 and δ=0.02. We assume all male calves are sold, i.e. $MCALF_t = SALE_t^{MCALF}$. Female calves that are retained become heifers so that:

(2) $$HEF_{t+1} = FCALF_t - SALE_t^{FCALF},$$

where $SALE_t^{FCALF}$ denotes the number of female calves sold. Heifers join the breeding stock in the following year so that:

(3) $$COW_{t+1} = (1-\delta)(COW_t - ADJ_t^{COW}) + BUY_t^{COW} - SALE_t^{COW} + (1-\delta)(HEF_t - ADJ_t^{HEF}),$$

where BUY_t^{COW} denotes cow purchases, $SALE_t^{COW}$ cull-cow sales, and ADJ_t^{HEF} emergency heifer-stock adjustment. We assume that replacement heifers are not purchased or sold (except for emergency adjustments). A 15% minimum cow culling rate is also imposed to account for declining productivity of older cows.

Fuel Accumulation

To characterize wildfire fuel accumulation and wildfire behavior in each rangeland state, we adopt "fuel models" that are used by fire behavior scientists and firefighting agencies (Anderson 1982). Each fuel model identifies vegetation types, including examples of typical plant species composition, and describes their characteristics as fuel (e.g. moisture content, volume per acre). Based on the fuel model definitions by the National Fire Danger Rating System of 1978 (Andrews and Bradshaw 1997), we use fuel model T to characterize state 1, fuel model B for state 2, and fuel model A for state 3 (Andrews and Bradshaw 1997).

In keeping with the fire science literature, we measure fuel stock f_t in terms of fuel bed depth (in feet). In particular, we assume that in the absence of fuels removal treatment, fuels accumulate according to a logistic growth function:

(4) $$f_{t+1} = f_t + \theta f_t \left(1 - \frac{f_t}{K}\right),$$

where θ denotes the intrinsic growth rate and K the carrying capacity for accumulated fuel. For each fuel model, information about the typical fuel bed depth is available from the U.S. Forest Service (USFS 1998). Using Anderson (1982), we select the carrying capacity K to be 120% of the typical fuel loading.[2] These figures are reported in Table 2. The intrinsic fuel growth rate θ for each rangeland state is calibrated such that, starting from 0.01 feet, the fuel grows back to the typical fuel depth after the average number of years between two successive fire events (or fire-return interval) for the specific rangeland state. The ranges of fire-return intervals for the rangeland states used in our study are taken from Stone (2010), and the midpoints of the intervals are used in the exercises in this article.

In implementation, we consider *average* fuel stocks for ranch size *l*. Assuming that fire and fuels treatment both reduce fuel stock to zero for the affected acreage, (4) is modified to characterize or average fuel stock $\bar{f}_t$:

(5) $$\bar{f}_{t+1} = \frac{l_t}{l}\left\{\bar{f}_t + \theta\bar{f}_t\left(1 - \frac{\bar{f}_t}{K}\right)\right\},$$

where

(6) $$l_t = l - u_t - \sigma_t y_t$$

is rangeland acreage available for grazing in year *t* (i.e. rangeland not affected by either fire or fuels treatments in year *t*), σ_t is the random number of wildfires on the ranch in year *t*, whose specification is discussed below, and u_t is acres treated for fuels removal. We assume that vegetation, and hence wildfire fuels, cannot be completely removed from the landscape, so that the lower bound of $\bar{f}_{t+1}$ is set at 0.1. This is not an unreasonable assumption because, given the seed bank of cheatgrass that is prevalent throughout the Great Basin, it is considered impossible to eradicate cheatgrass from this area (Noss et al. 1995; Chambers et al. 2007).

Fire Size

The size of a fire y_t for a given rangeland state in year *t* is a function of average fuel depth[3]

(7) $$y_t = FS1\bar{f}_t^{FS2}$$

where y_t is in thousands of acres burned. Coefficients *FS*1 and *FS*2 are calibrated for each rangeland state so that the mean observed fire size is obtained at typical fuel depth and the fire size of the largest 95 percentile is obtained at the fuel depth carrying capacity *K*.[4] Data for all wildfires in Western Great Basin (Western Great Basin Coordination Center) between 2000 and 2007 for relevant fuel types (T, B, and A) and elevation (below 6,700 feet) are used for the calibration. The total area on the ranch burned in year *t* is the product of the number of fire events σ_t and the size of each fire y_t.[5]

Stochastic Fire

The probability distribution of the stochastic factor σ_t, which describes the total number of fires on the ranch in a given year, is derived as follows. First, we divide the ranch into "fire cells," with the size of each cell corresponding to the average size of a wildfire in the relevant rangeland state. The number of cells accommodated on a ranch is rounded to the nearest integer. For example, in state 1 the average size of a wildfire is 1,276 acres, so a 5,000-acre ranch can contain 3.91 cells but we round it to four fire cells. Second, we assume that each fire cell can have at most one fire per year. Third, we calculate the probability of a wildfire in each cell in a given year using the fire-return interval (Table 2) in each rangeland state, assuming that the probability of wildfire in a given year is independent of wildfire activity in the fire cell in any previous year (i.e. assuming geometric probability distribution for wildfire occurrence). Under this assumption, if the fire-return interval in a rangeland state is *T* years, then the probability of fire in each cell in a given year is *1/T*. Forth and finally, the total number of wildfires on a ranch in a given year is calculated under the assumption that fire occurrence in any one cell is independent of fire occurrence in any other cell. This assumption implies that the number of wildfires on a ranch in year *t* follows the binomial distribution

(8) $$Prob(\sigma_t = r) = \binom{n}{r} p^r (1-p)^{n-r},$$

where *r* is the number of wildfire events, *n* is the number of fire cells on the ranch, and p=1/*T* is the annual probability of wildfire in each cell. The average number of fires for each ranch size in each rangeland state given these assumptions is listed in Table 1.[6]

Fire Suppression Cost

The relationship between fire size y_t and fire suppression expenditure c_t^f is estimated using data on Great Basin wildfires compiled by the USFS Rocky Mountain Research Station.

Observations that correspond to fuel models T, B, and A, elevation below 6,700 feet, and for the period of 2000 and 2007 are used (n=76). A polynomial equation that goes through the origin

(9) $$c_t^f = FF1{y_t}^2 + FF1y_t = -0.4507{y_t}^2 + 117.6240y_t$$

is fitted (in \$000 and y_t in thousand acres; R^2=0.449) to the data.

In calculating total fire suppression costs, however, we take into account the observed skewness in fire-size distribution because extremely large fires represent the vast majority of the public wildfire suppression expenditures. Holmes, Huggett, and Westerling (2008) report that 94 percent of fire suppression costs on US forest service land during 1980-2002 resulted from 1.4 percent of the fires. In the Western Great Basin fire data, for example, on average the largest fires in state 1 (fuel model T) are 65.97 times larger than the average fire, but they represent only 1.15% of all state 1 fires (Table 3). Across all rangeland states, the size of the vast majority of the fires is below average, and the largest fires represent less than 2% of all fires (Table 3).

To account for the skewness in the fire-size distribution, we make the following assumptions when calculating the relationship between total acres burned on a ranch, $\sigma_t y_t$, and wildfire suppression costs. First, we assume that there are three fire sizes: a "small" fire is defined as smaller than the mean of all fires; a "large" fire is defined as between the mean of all fires and the mean of all above-mean fires; and an "extra large" fire is defined as larger than the mean of all above-mean fires. Second, we calculate wildfire suppression costs for each of the three fire sizes by scaling the predicted fire size y_t given fuel stock level $\bar{f}_t$. Third, we add up total wildfire costs assuming that the proportion of fires in each size class in a given year is fixed.

Revenue, Cost, and Discount Rate

Ranch revenue is derived from cattle sales. We assume that cattle prices are deterministic. The prices for different animal classes are specified according to prices used in enterprise budgets for

cow-calf ranches in the region (University of Nevada Cooperative Extension Fact Sheets, various issues). The unit sale prices for male calves, female calves, and cull cows used in this study are \$680 ($SALE_t^{MCALF}$), \$578 ($SALE_t^{FCALF}$), and \$496 ($SALE_t^{COW}$). For emergency adjustments ADJ_t^{COW} and ADJ_t^{HEF}, a 20% discount is imposed on the prices of $SALE_t^{COW}$ and $SALE_t^{FCALF}$ to prevent unrealistic arbitrage across periods. Given the fire-related parameter specification, there are possibilities that an entire ranch can burn in a year under the 1,500-acre ranch scenario. Therefore, the ability of a producer to resume ranching after a devastating fire by purchasing brood cows becomes important. We specify the price of brood cow twice as high as that of cull cow.

Based on the same enterprise budget estimates, we estimate that the cost of supplementary feeding is \$29 per cow per month under the typical grazing and feeding regime in this region: 7-8 months of grazing on natural rangelands and 5-7 months of supplementary feeding. This is a low-productivity cattle grazing system, where the stocking capacity is estimated between 0.001 and 0.128 cows per acre.[7] Assuming that the current rangeland condition in the region is no worse than state 2, we assign the two end values as the necessary supplementation length to maintain cattle productivity in state 1 (5 months) and state 2 (7 months). On the other hand, state 3 range is considered far less productive for cattle grazing. Since cheatgrass seeds are harmful to cattle, the window for grazing on state 3 rangelands is limited to about two weeks in spring before seeding and about six weeks in the fall after cheatgrass having given off seed (Schmelzer et al. 2008). Accordingly, we assume that under state 3 grazing is possible for 2 months and cattle need to be fed with supplements for 10 months to maintain cattle productivity. In this article the stocking capacity is held constant at 0.128 cows per acre. The left hand side of the grazing availability constraint (2) is replaced with total animal units (cow-equivalent units) in the

grazing season, calculated by applying animal unit conversion rates of 0.5 for a calf and 0.75 for a heifer. Total animal units fed with supplements are calculated in a similar manner.

Additional herd maintenance costs are applied to animals that survive the winter. Again using data from the University of Nevada Cooperative Extension Fact Sheets, a linear cost curve $PC1 + PC2AU_t = 31.752 + 0.1354AU_t$ (in \$000, AU_t is animal units) is fitted to estimate the relationship between herd size and herd maintenance costs. In this article, however, we drop the intercept $PC1$ or the annual fixed cost so that there are no scale economies in the model. Disregarding scale economies allows us to focus on the relationship between ranch size and the rancher's ability to adjust production in the presence of stochastic wildfire. While disregarding fixed costs changes the levels of annual profits and thus the objective function values, it does not influence the marginal conditions and, hence, the rancher's tradeoffs between current period grazing and future wildfire risk that is central to our exercise are unchanged.

We systematically vary per-acre fuels treatment costs to investigate the potential incentives for private ranchers to engage in fuels treatment. Actual costs of fuel/invasive weed treatment and its efficacy depend on methods used. We use a low-cost method of herbicide application at \$20 per acre as a benchmark and then consider subsequently reduced treatment costs. In doing so we evaluate effects of policies that might be offered (such as cost sharing and subsidization) to induce rancher efforts to reduce the social costs of wildfire. Finally, we set the discount rate r at 10%.

Objective Function and Solution Technique

Assuming risk-neutrality, the rancher's decision problem of is represented as:

(10) $\max \mathrm{E}_0[\sum_{t=0}^{\infty}(1+r)^{-t}\pi_t]$, s.t. C

by choosing in each period cattle sales and fuels treatment level, where $\mathrm{E}_0[\cdot]$ is the expectation operator with the expectation formed at the beginning of the planning time horizon, r is the discount rate, and π_t is the annual profit composed of ranch revenue minus costs of feeding, herd maintenance, and fuels treatment as discussed in the previous subsection. In the case of social planner's decision problem, an additional cost of fire suppression defined in equation (9) is incorporated in π_t. The problem (10) is subject to a set of constraints *C*, which includes cattle population dynamics (1)-(3), fuel accumulation dynamics (5), annual grazing land availability constraint (6), and fire-size equation (7).

We consider that the decision maker updates information as it becomes available to him about occurrence of fires, herd size, and the fuel stock to make ranch management decisions each year. Accordingly, we consider a closed-loop system, where feedback occurs through new information summarized in the current level of state variables in each period. With this assumption, the solution to (10) can be obtained using a stochastic dynamic programming (SDP) solution technique. The resulting Bellman equation for problem (10) is:

(11) $V(\boldsymbol{x}_t, f_t; \sigma_t) = \max\{\pi_t + (1+r)^{-1}\mathrm{E}_t[V(\boldsymbol{x}_{t+1}, f_{t+1}; \sigma_{t+1})]\}$, s.t. *C*,

where $\boldsymbol{x}_t$ is a vector of cattle stock (COW_t and HEF_t) and $V(\cdot)$ is the value function.

In numerical implementation, we use a value function approximation approach (Judd 1998; Miranda and Fackler 2002), where the unknown value function $V(\cdot)$ is approximated with a polynomial and then the problem (11) is solved forward in time to obtain cattle sales and treatment levels for each time period, following the steps outlined in Kobayashi et al. (2007). We solve the problem using a simulated time-series for fire events, randomly generated according to corresponding fire-size probability distributions. Each simulation is implemented for 100 years.

Model Results

In this section, we present the results from our model. Initial cow stock is specified to be 75 for the 1,500-acre ranch (scenario (a)), 250 for the 5,000-acre ranch (scenario (b)), and 12,000 for the 240,000-acre ranch (scenarios (c) and (d)). In all scenarios, the initial heifer stock is 25% of initial cow stock, and the initial fuel stock is the typical fuel depth for the relevant rangeland state from Table 2. Model results under each decision-maker scenario and each rangeland state are summarized in Table 5. While they are analyzed in detail in the subsequent subsections, a summary of the results are the following. As expected, it is optimal to maintain a larger herd under state 1 than under state 2. Under state 3, the ranching operation is liquidated immediately or after a brief phase-out period. Under the 1,500-acre ranch scenario or scenario (a), the entire ranch can burn in a year, and the resulting optimal herd-size patterns are distinctly different from those under larger ranch scenarios or scenarios (b) and (c). At the cost of $20 per acre, no treatment is optimal for scenarios (a)-(c). Only when the costs of wildfire suppression are internalized in the decision making, application of fuels treatment becomes optimal, though only under less desirable rangeland states. Consequently, the optimal herd size patterns under scenario (d) are also distinct from those under scenarios (b) and (c) in states 2 and 3.

Rangeland State and Optimal Herd Dynamics

In our model, rangeland state influences ranch operations in two ways. First, the rancher must compensate for the reduced range productivity in states 2 and 3 relative to state 1 with increased supplementary feeding. Second, rangeland state influences frequency and size of wildfire. Our results confirm that rangeland state influences a rancher's herd management decisions and ranch profits. We find that average herd size and annual ranch profit are consistently higher in state 1 than in state 2 (Table 5). In state 3, the ranching operation is not profitable due to the short

grazing season and high costs of supplementary feeding: in all scenarios the ranch operations in state 3 are either liquidated immediately or after a brief phase-out period. For this reason, annual profits are not reported for state 3 in Table 5.

We find that wildfire influences both the absolute level of herd size and dynamic patterns of herd management. It is optimal for the rancher to maintain a larger but more volatile herd size in state 1, while a smaller but more stable herd size is optimal in state 2. Figure 1 illustrates these patterns for scenario (b). Similar patterns are observed for scenarios (a) and (c). In state 1, the rancher maintains a large herd so that each fire event, though infrequent (there is one fire per year in years 7, 27, 32, 36, 41, and 68 in the example in Figure 1), causes the rancher's grazing land availability constraint to bind and leads to large herd size reduction. In contrast, in state 2, where fire occurs more frequently and the rancher maintains a smaller herd, the optimal herd-size path does not appear to be influenced by fire events. We argue that this is because more frequent wildfires make the expected opportunity cost of heifer retention higher under state 2 than under state 1 and overall value of the herd higher in state 1. Heifer retention is an investment for future herd maintenance and expansion. When fire occurs more frequently, attempts to expand the herd would more often be met with forced herd reductions due to fire events. Therefore, more frequent wildfire makes it an attractive strategy to maintain a small but stable herd size.

The oscillating herd size movement under state 2 is a result the systematic inter-temporal balancing of heifer-calf retention and sales. In this particular case, all heifer calves are sold in one year for immediate revenue followed by retention of a large proportion of heifer calves to compensate in the following year. This is in part a result of model rigidity where variation in

heifer and cow productivity is ignored. Also, the assumption of expected profit maximization objective drives this result: a risk-averse rancher would not take this risky practice.

Ranch Size and Optimal Herd Dynamics

Our results confirm that a rancher's herd management decisions and ranch profits in the presence of wildfire depend on ranch size. As expected, we find that without fuels treatment,, a similar proportion of total ranch area is burned each year across the different ranch sizes: 3-4% in state 1, 4-7% in state 2, and 9-23% in state 3.[8] However, the year-to-year variability in the percentage of total land available grazing land, l_t/l, is larger for smaller ranches. The coefficient of variation for l_t ranges 0.174-0.207 under scenario (a), 0.131-0.178 under scenario (b), and 0.015-0.020 under scenario (c) (Table 5). This indicates that, on average, downside shocks to grazing land availability due to wildfires are proportionately larger for smaller ranches.

The results indicate that, as was the case with the differences in herd management patterns across rangeland states, the differential expected value of herd results from different ranch sizes. Because the shocks to grazing land availability are proportionately smaller for larger ranches, the expected marginal value of the herd would be greater on a larger ranch. As such, we would expect that herd size per acre would be greater in scenario (c) compared to scenario (a) or (b). This expectation is confirmed in Table 5, where average herd-size and average annual profits are higher in scenario 3. As there are no scale economies in production in our model, the increasing returns to rangeland acreage arise because a large ranch have the ability to cushion the grazing land availability shocks from wildfire "across space" and thus are less likely to be forced to make dramatic adjustments.

Incentives for Fuels Removal Treatment

The model implies that at $20 per acre, which roughly is the cost of herbicide application per acre, it is not optimal for private rancher (scenarios (a)-(c)) to invest in fuels removal treatments. This is consistent with the observation that private implementation of fuels treatment is not typical in the Great Basin. Given the discussions in the previous subsection on the relationship between ranch size and a rancher's ability to adjust production after a wildfire, we expect that smaller ranches have a stronger incentive to implement fuels treatment if the treatment cost is lower. To investigate this hypothesis, we run the model with a lower cost of fuels treatment. The results indicate that under the aggregate rancher scenario or scenario (c), fuels treatment is never optimal for all rangeland states even at no cost. This is because the opportunity cost of lost grazing land as a result of treatments is still greater than the expected benefits the rancher receives from treatments given the assumptions in our simulations.

In state 3 in scenario (c), however, availability of fuels treatment at no cost increases the expected profits from ranching and it is now optimal to continue ranching, with an average herd size of 12,673 cows. This is because, even when no treatments are undertaken, a reduced cost of treatment lowers the expected cost of substantial losses in grazing land (many wildfires in the same year) to the aggregate rancher. The lower expected cost of substantial losses of grazing land in turn makes the aggregate rancher more willing to bear the risk of maintaining a larger herd in the presence of wildfire and makes the operation more profitable.

In contrast, for smaller ranches, fuels treatments are implemented when treatment cost is reduced to a sufficiently low level. For scenario (b), treatment becomes optimal at the cost of approximately $1.00 in state 1 and approximately $0.25 in state 2. For scenario (a), treatment becomes optimal at the cost as high as $18.00 in state 1 and $2.00 in state 2. Importantly, we

find that a rancher's reservation price for fuel treatment is higher when the range productivity is higher.

Figure 2 illustrates the dynamics of optimal herd size and fuel stock when treatments are available at the cost of $1.00 per acre for scenario (b) in state 1. The rancher optimally applies treatments every 3-4 years and the fuel stock is maintained around one foot. By undertaking fuels management, the rancher reduces the size of wildfires relative to the case without treatment, thus making the available grazing area larger and more stable each year, thereby allowing the rancher to maintaining a larger and more stable herd size.

Fire Suppression Cost Externality

Finally, we find that, when wildfire suppression cost is internalized in aggregate rancher's decision making (scenario (d)), treatment becomes optimal at the default cost $20 per acre in states 2 and 3. As is shown in Table 5, rows (c) and (d), the benefits to society of optimally applying fuels treatments are substantial in terms of reduced wildfire size and suppression expenditure. In state 2, the average annual fire suppression expenditure is reduced by 5% (from $1.36 to $1.30 million) due to optimal fuels treatments, achieving a 12% higher net present value from the rangeland over the 100-year simulation period compared to scenario (c) where suppression costs are not internalized by the aggregate rancher (from NPV2 of -$2.54 to -$2.26 million). In state 3, the benefit of fuels treatment is even greater; annual fire suppression cost is reduced by 96% (from $3.08 to $0.13 million) and the net present value of rangeland is increased by 45% (from -$40 to -$22 million). Note that wildfires will continue to occur and fire suppression efforts will continue to be needed even if the ranch operation is liquidated.

Summary and Conclusions

In this article we present a bio-economic model of a cow-calf ranch operation on Great Basin rangeland and solve it numerically using a stochastic dynamic programming (SDP) solution technique. We use the model to analyze how a profit-maximizing producer's optimal levels of production and fuels treatment to reduce the risk of wildfire are influenced by rangeland ecological conditions and ranch size. One scenario of the model implementation includes wildfire suppression costs in decision maker's objective. These costs are incurred by the public agencies and are external to private ranchers' decision making. We compare results from this scenario with the scenarios where the rancher does not internalize the costs of wildfire suppression to characterize the nature of external costs. We parameterize the model to generate representations of "more-favorable" and "less-favorable" production environments. These differences in the production environment are due to differences in the ecological state of the rangeland, ranch size, and the cost of implementing fuel treatment.

The two main findings of this article are the following. First, the marginal value of the cattle stock is higher and the optimal herd size is larger for a producer operating in a more favorable production environment. This is because a more favorable production environment has a lower costs of supplementary feeding, a lower frequency and severity of wildfire occurrences (the latter is endogenous), and a larger amount of grazing land that provides the rancher with a "buffer" in the event of wildfire-induced restriction on land availability. On the other hand, herd expansion is discouraged in a less favorable environment chiefly because of the higher probability that the cattle would have to be sold off to meet the reduced grazing land availability due to wildfires.

The effect of ranch size on herd size and ranch profits deserves special note. We find in the model that the downside shocks on available grazing land due to wildfires are proportionately

smaller for larger ranches and that larger ranches exhibit a greater ability to adjust production in response to wildfires. This implies a potential source of increasing returns to scale in ranch operation in presence of wildfire risks. This observation suggests that an institutional arrangement such as grazing land banks, in which ranchers who had invested in fuels treatments would have access to reserved grazing lands in the event of wildfires could spread the downside risk of wildfires among participating individuals. This type of institution would allow individual ranchers to maintain larger herds and achieve higher profitability than would be possible otherwise.

The second important set of results has to do with incentives to invest in fuels removal treatment. We find that private incentives for implementing fuels treatment is higher for more productive rangeland states, while the opposite result is obtained when wildfire suppression costs are internalized into the decision problem. For private ranchers, the marginal benefit of treatment is higher in more favorable production environments. We also find that the marginal benefits of fuels treatments are lower for larger ranches than for smaller ranches because of the higher capacity of larger ranches to mitigate some of the costs of wildfire due to a looser constraint on grazing land availability. On the other hand, because wildfire frequency and severity and suppression costs are greater for more degraded ecological states, the marginal social benefit of treatment increases with degradation. Subsidized treatment costs would encourage private ranchers to invest more in fuels removal treatments; however, subsidization would lead to the greatest increases in fuels removal treatments on healthy rangeland where the societal benefits from treatment are the lowest. For this reason, subsidization may not achieve a target level of fuels reduction unless the subsidies are directed towards degraded rangeland.

As illustrated in this article, this model can be used to analyze a wide variety of questions that are of interests to both researchers and public land managers responsible for planning and

implementing programs to reduce social costs of wildfires. However, these findings must be considered preliminary. First, the results are obtained for the three rangeland states by using three sets of parameters describing rangeland productivity (and accordingly feeding cost), wildfire frequency, and fuel accumulation dynamics. In other words, in each model run, we impose a rangeland state and assume the state would never change. In reality, however, the progression through ecological states from state 1 to state 2 and then to state 3 is an on-going dynamic process, which is not reversible without large external and costly inputs. This implies that the decision to invest in fuels treatment or to take other range conservation efforts (e.g. grazing pressure reduction) affects the probability of an irreversible switch into more degraded ecological state. The magnitudes of the values of fuel treatments are likely underestimated in the current model, because the marginal cost of the increased probability of an irreversible ecological switch is not included. Thus, future work will introduce the dynamics of ecological states, i.e. connecting states 1, 2, and 3.

Second, the costs of wildfire suppression are one of the many external costs of wildfire. Additional external cost of wildfire includes damage to property, cost human health from released smoke and particulate matter, cost of releasing carbon sequestered in rangeland soils and plants. Moreover, wildfire is one of the many external costs associated with rangeland degradation and invasive weeds. Additional external costs of invasive weeds include reduced wildlife habitat quality, increased soil erosion, and reduced quality of recreational experience. Again, when these other external costs are incorporated in the social planner's objective function, the value of treatment would increase.

Third, the current model also does not incorporate the dual nature of the effect of grazing. Livestock grazing has a negative impact on the resilience of the native vegetation in the healthier

ecological states, while grazing serves as a fuel reduction tool in the degraded states by reducing accumulated dead biomass of invasive annual grasses (i.e. fuel for rangeland wildfires) (Davidson 1996). These negative and positive effects of livestock grazing are not currently modeled. When these features are included in the model, total liquidation of cattle in state 3 may not be socially optimal solution, as is predicted in the current model, because grazing can serve to reduce the social costs of fire suppression through reducing accumulated fuels. In the case where ranching is not financially viable, but still provides a societal benefit in terms of fuels management, the optimal levels of grazing would require a subsidy or some other incentive be provided to induce private ranchers to graze state 3 rangelands.

Finally, also important is the spatial externalities related to wildfire. Spatial externalities arise because once ignition occurs, wildfire moves to other contiguous areas depending, among other things, on prevailing wind speed and slope. Such spatial externalities are likely to affect the relationship between ranch size and a rancher's incentive to engage in fuels treatments. Although spatial externalities cannot be explicitly incorporated into the current modeling framework, future work to modify the current model could allow such inferences.

Footnotes

[1] On public rangelands in the western United States, ranchers face a mandatory two year moratorium on grazing after a wildfire to allow for the fire-damaged rangeland to rehabilitate itself (Bruce 2007).

[2] Sandy Gregory, Fuels Specialist for the Nevada State BLM, personal communication.

[3] The shape of the fire-size curve is determined based on the prediction of the fire behavior simulation model BehavePlus (Andrews 1986; Andrews and Chase 1989; Burgan and Rothermel 1984; Andrews and Bradshaw 1990).

[4] The fires considered in this article are larger than in Kobayashi and Rollins (2009), where only fires that are contained in a day were considered.

[5] We calibrate (7) using the 95 percentile wildfire because the largest 5% of the distribution contain extremely large wildfires (Holmes, Huggett, and Westerling 2008). Including these large wildfires in our calibration of (7) would cause us to predict an unrealistically large wildfires for typical but above average fuel loads. The assumption of the power-function functional form in (7) was validated using the behavior simulation model BehavePlus (Andrews 1986; Andrews and Chase 1989; Burgan and Rothermel 1984; Andrews and Bradshaw 1990).

[6] A second approach to deriving σ_t was also implemented, where we use historical data of wildfires in Western Great Basin (Western Great Basin Coordination Center) and the information about Sage Grouse habitat as a proxy for the proportion of the area in each of the three rangeland states (NDOW 2004). The two approaches resulted in the expected fire numbers that are very similar to each other for state 1, thus we place a fair level of confidence for the parameter value for this state. However, the divergence of the obtained expected fire numbers under the two sets

of assumptions is large for states 2 and 3. In this article we use the fire number distribution derived from the first approach, we will further refine this parameter.

[7] It is determined by the assumption of maximum forage production of 800 lbs per acre, with a cow consuming 800 lbs of forage per month (Sherman Swanson, Range and Riparian Extension State Specialist for University of Nevada Cooperative Extension and Scientist for Nevada Agricultural Experiment Station, personal communication), for a total of 7.8 months each year (enterprise budgets). This gives a minimum requirement of 7.8 acres per cow, or maximum capacity of 0.128 cows per acre.

[8] Results are not shown in the table but can be calculated using $\bar{l}_t$. The smaller variation in the burned proportion for scenario (a) than scenario (b) in state 3 is due to the lower average fuel stock levels that result from frequent complete burns of the entire ranch in scenario (a).

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Table 1. Decision-Maker Scenarios

	Decision-maker scenario			
	(a) Individual rancher	(b) Individual rancher	(c) Aggregate rancher	(d) Social planner
Rangeland	1,500 acres	5,000 acres	240,000 acres	240,000 acres
Herd	1 herd	1 herd	1 herd	1 herd
Objective	Ranch income	Ranch income	Ranch income	Ranch income minus fire suppression cost
Average number of fires in each year[a]				
State 1	0.026	0.087	4.181	4.181
State 2	0.163	0.544	26.105	26.105
State 3	0.816	2.719	130.532	130.532

[a] Obtained using average fire size and annual fire probability (Table 2) and adjusted for ranch size.

Table 2. Fuel and Fire Parameters Used in this Study

	State 1	State 2	State 3	Data source and notes
Fuel model	T	B	A	Andrews and Bradshaw (1997)
Typical fuel depth (feet)	1.25	4.50	0.80	USFS (1998)
Maximum fuel depth *K* (feet)	1.50	5.40	0.96	Assumed based on Anderson (1982)
Intrinsic fuel growth rate θ	0.1470	0.5266	1.2377	Calibrated
Fire-return interval (years)	45	15	5	Stone (2010)
Annual fire probability	0.022	0.067	0.200	Calculated using fire-return interval
Fire size coefficient FS1	0.7457	0.0072	0.6846	Calibrated
Fire size coefficient FS2	2.4059	2.9526	2.7850	
Average fire size (000 acres)	1.276	0.613	0.368	Western Great Basin Coordination Center
Largest 95 percentile fire size (000 acres)	1.978	1.050	0.611	

Table 3. Size Distribution of Wildfires[a]

	Scale[b]	Proportion	n
State 1 (Fuel model T)			
Small	0.0294	0.9428	3,197
Large	4.6715	0.0457	155
Extra Large	65.9708	0.0115	39
State 2 (Fuel model B)			
Small	0.0490	0.9172	155
Large	1.8517	0.0651	11
Extra Large	47.0146	0.0178	3
State 3 (Fuel model A)			
Small	0.0383	0.9403	662
Large	4.8915	0.0455	32
Extra Large	52.2099	0.0142	10

Source: Western Great Basin Coordination Center

Notes:

[a] A "small" fire is defined as smaller than the mean of all fires; a "large" fire is defined as between the mean of all fires and the mean of all above-mean fires; and an "extra large" fire is defined as larger than the mean of all above-mean fires.

[b] Average within each class (small, large, extra large), relative to the mean of all fires.

Table 4. Additional Parameters Used in this Study

Parameter	Value
Net reproduction rate β	0.8075
Mortality rate δ	0.02
Minimum culling rate	15%
Bull calf price	$680/head
Heifer calf price	$578/head
Cull cow price	$476/head
Emergency sale discount	20%
Brood cow price	2 times cull cow price
Feeding cost per head per year	
State 1 (5 months)	$145
State 2 (7 months)	$203
State 3 (10 months)	$290
Production cost coefficient PC1	(31.752)[a]
Production cost coefficient PC2	0.1354
Stocking capacity	0.128 cows/acre
Cow-equivalent unit of calf	0.5
Cow-equivalent unit of heifer	0.75
Fuels treatment cost	$20/acre
Firefighting cost coefficient FF1	-0.4507
Firefighting cost coefficient FF2	117.6240
Discount rate	0.1

[a] Set equal to zero in numerical implementation.

Table 5. Summary Results of Benchmark Runs

		State 1	State 2	State 3
(a)	1,500-acre individual rancher	• Volatile herd size around 71 cows (sd 16.23) • NPV=91.18 • $\bar{\pi}_t$=9.12 (sd 15.35) • $\bar{l}_t$=1.440 (sd 0.295, cv 0.205)	• Volatile herd size around 34 cows (sd 11.92) • NPV=5.69 • $\bar{\pi}_t$=0.46 (sd 13.87) • $\bar{l}_t$=1.433 (sd 0.249, cv 0.174)	• Immediately liquidate all cattle • NPV=36.72 • $\bar{l}_t$=1.364 (sd 0.282, cv 0.207)
(b)	5,000-acre individual rancher	• Volatile herd size around 195 cows (sd 27.92) • NPV=359.90 • $\bar{\pi}_t$=28.03 (sd 18.91) • $\bar{l}_t$=4.840 (sd 0.695, cv 0.144)	• Stable[a] herd size around 141 cows (sd 21.63) • NPV=241.68 • $\bar{\pi}_t$=13.23 (sd 5.53) • $\bar{l}_t$=4.645 (sd 609, cv 0.131)	• Phasing out and total liquidation • NPV=158.89 • $\bar{l}_t$=3.826 (sd 0.680, cv 0.178)
(c)	240K-acre aggregate rancher	• Volatile herd size around 12,272 cows (sd 100.50) • NPV=19,342.02 • $\bar{\pi}_t$=1,940.66 (sd 61.84) • $\bar{l}_t$=230.082 (sd 4.587, cv 0.020) • NPV2=13,714.63 • $\bar{c}_t^f$=576.73 (sd 267.79)	• Stable[a] herd size around 6,851 cows (sd 622.69) • NPV=11,595.72 • $\bar{\pi}_t$=643.98 (sd 253.59) • $\bar{l}_t$=226.715 (sd 3.458, cv 0.015) • NPV2=-2,539.38 • $\bar{c}_t^f$=1,364.26 (sd 352.73)	• Phasing out and total liquidation • NPV=7,699.71 • $\bar{l}_t$=211.245 (sd 4.168, cv 0.020) • NPV2=-40,005.39 • $\bar{c}_t^f$=3,077.83 (sd 438.20)
(d)	240K-acre social planner	• Treatment not optimal • Identical to aggregate rancher's ranch output • NPV=13,714.63 • $\bar{l}_t$=230.082 (sd 4.587, cv 0.020) • $\bar{c}_t^f$=576.73 (sd 267.79)	• Phasing out and total liquidation • Treatment only in first 2 years • NPV=-2,263.86 • $\bar{l}_t$=225.082 (sd 15.892, cv 0.071) • $\bar{c}_t^f$=1,297.58 (sd 388.80)	• Liquidate ranching operation in year 2 • Treatment every other year • NPV=-21,908.44 • $\bar{l}_t$=122.521 (sd 118.047, cv 0.963) • $\bar{c}_t^f$=125.64 (sd 296.21)

Notes:

- Each cell represents one run for 100 years with initial cow stock of 75 in (a), 250 in (b), and 12,000 in (c) and (d). In all models, the initial heifer stock is 25% of initial cow stock, and the initial fuel stock is the typical fuel depth in Table 2.
- NPV = discounted sum of annual profits over 100 years ($000); $\bar{\pi}_t$ = average annual profit ($000); $\bar{l}_t$ = average area available for grazing per year (000 acres); $\bar{c}_t^f$: average annual fire suppression cost ($000); NPV2 = discounted sum of aggregate rancher's annual profit minus fire suppression cost. Average herd size and profit are calculated for the period after the initial herd size adjustment.
- sd = standard deviation; cv = coefficient of variation.

[a] Cyclical herd size movements around a stable mean.

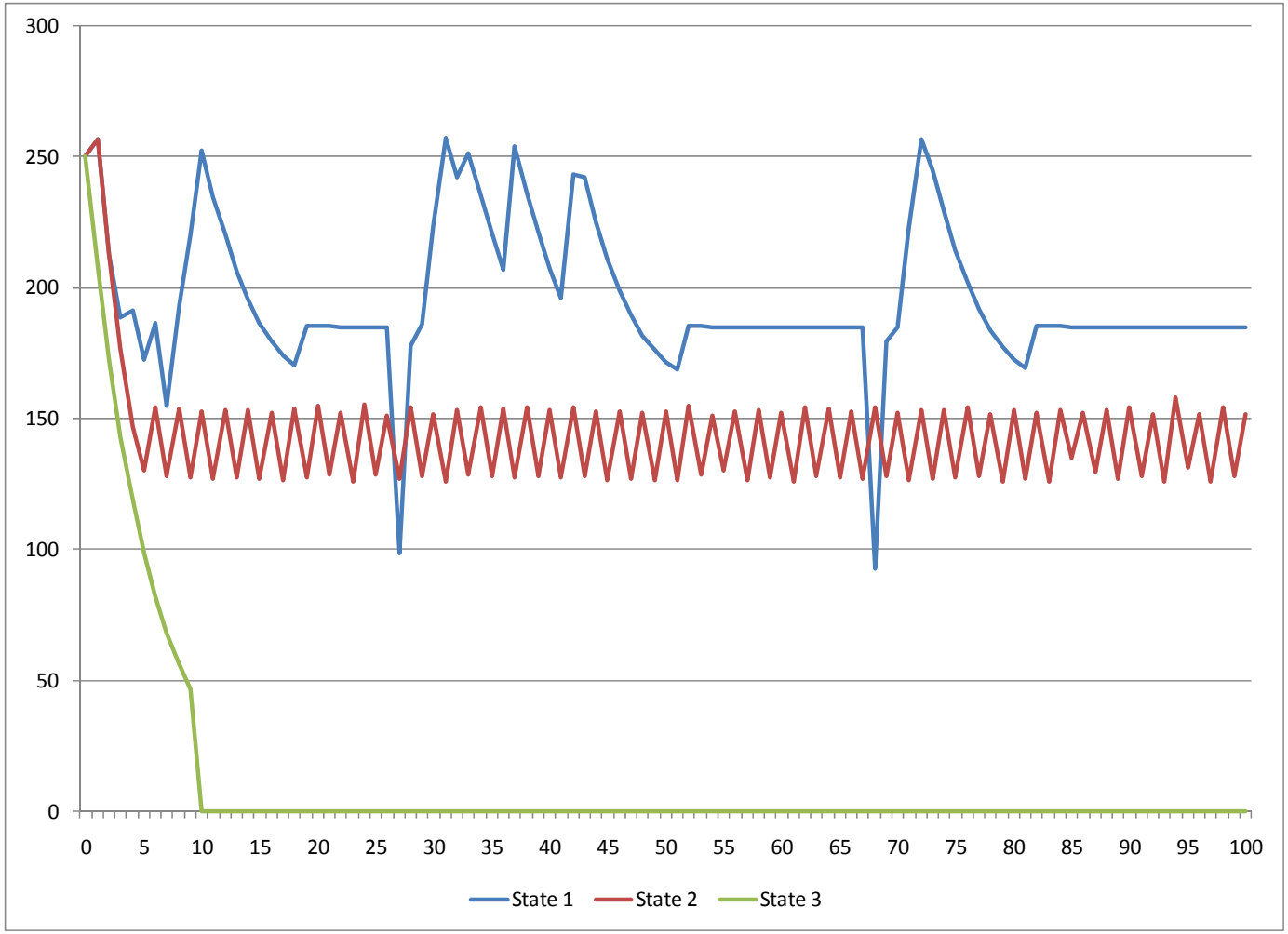

Figure 1. Optimal Cow Stock Dynamics on 5,000-acre Individual Ranch

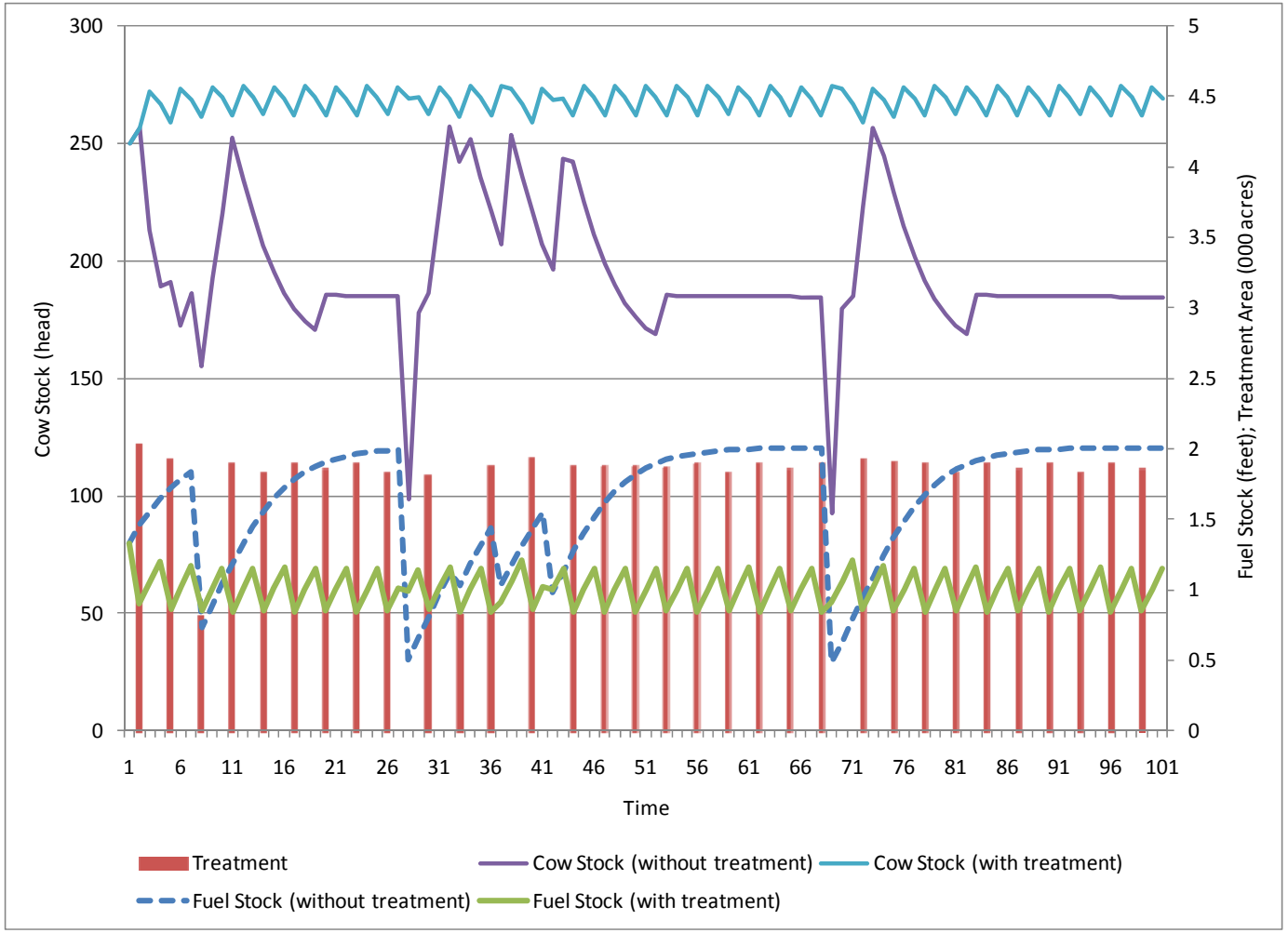

Figure 2. Optimal Treatment Strategy and Fuel and Cow Stock Dynamics under Treatment Cost Subsidy (5,000-acre ranch, state 1, treatment cost = $1.00/acre)