Invasive Weeds, Wildfire, and Rancher Decision Making in the Great Basin

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Introduction

Efficient grazing with ecosystem management is an ever-growing concern on Great Basin rangelands due to threats presented by interrelated problems of invasive weeds and wildfire. The sagebrush biome, comprising some 100 million acres of western high desert, is a complex native plant community of woody shrubs and perennial grasses that supports domestic livestock grazing and the rural ranching economy of this region. Much of the land is federally owned and managed by public agencies, with a large proportion privately ranched through grazing leases. Today, about half of the sagebrush biome is dominated by invasive annual grasses, primarily cheatgrass (*bromus tectorum*). These invasive annual grasses produce heavy accumulations of highly flammable fine fuels, resulting in increasingly severe and frequent wildfires.

Available land treatment options include 1) pre-fire treatments consisting of herbicide application to target annual weeds in winter and early spring, prescribed burning, and mechanical removal of accumulated fuels, and 2) post-fire restoration treatments such as reseeding with vegetation to compete with invasive plants. Pre-fire treatments are proactive, less expensive, and have higher success rates than post-fire restoration. However, current public lands policies tend to be reactive in that they focus on post-fire rehabilitation. Private ranchers appear to have incentives to proactively control invasive weeds and fuel loads on their public rangeland allotments, but high transactions costs involved in obtaining permits necessary to implement such treatments seem to preclude private efforts. With ranchers having an advantage over public land managers in routine monitoring of range conditions, improved rancher decision flexibility through reduced transactions costs could result in timelier fuels treatments, which would contribute to improved rangeland quality and reduced public expenditures on firefighting in the long run. A new approach to efficient management of the Great Basin public rangelands may involve a close cooperation between public land managers and private ranchers.

The question we address in this article is: if ranchers were permitted to implement proactive land treatments, what would be the nature of tradeoffs they would face? To address this question, we construct a bio-economic model of rancher decision making and solve it numerically using a stochastic dynamic programming (SDP) solution technique. The model characterizes the technical tradeoffs ranchers face by incorporating the dynamics of invasive weeds and wildfire interactions with the dynamics of cattle reproduction.

Methodological contributions of this article lie in the treatment of invasive weeds and wildfire interactions with cattle herd dynamics. It is important to consider these in a unified framework because the opportunity costs of land treatment changes depending on herd size and available land, which is influenced by wildfire. Wildfire is in turn affected by the rancher's land treatment decision. To our knowledge, interactions between grazing intensity, control of invasive annual weeds, and stochastic wildfire events have not been studied in the context of ranchers' decisions regarding rangeland use. Eiswerth and van Kooten (2002) and Niell et al. (2008) analyze land treatment strategies with discrete-state models, where grazing plays no role. Huffaker and Cooper (1995), Hu et al. (1997), Janssen et al. (2004), and Finnoff et al. (2008) model long-run ecological impacts of grazing. Huffaker and Cooper (1995) study a similar system with native perennials and invasive annual cheatgrass, but wildfire is included only as an exogenous factor over which the decision maker has no control. Janssen et al. (2004) incorporate fire as an endogenous variable in their model of rangeland management, but use fire as a prescribed land treatment strategy with a perfectly predictable and beneficial outcome. This is unrealistic for modeling destructive wildfire events and invasive plant interactions on Great Basin rangelands.

Moreover, previous economic studies of interactions between livestock grazing and long-run rangeland quality 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 play an important role in understanding rancher incentives and thus for designing appropriate policies for range management. Relative to stocker operations, adjustments in herd size for cow-calf operations are more difficult, since herd-size increases occur through the slow process of biological reproduction or through finding breeding stock with desirable genetic traits. This "stickiness" in production adjustments is expected to affect rancher decisions on invasive weed/fire management. The purpose of this article is to shed light on tradeoffs between rancher profit and range-conservation motives by comprehensively treating factors affecting the dynamics of Great Basin rangeland ecology and cattle production.

Building on the technique presented in Kobayashi et al. (2007), we develop a continuous-state SDP model for a cow-calf operation. The rancher is assumed to maximize the expected net present value of his enterprise, where each year cattle are reproduced, raised, and sold on a fixed area of rangeland. Cow and heifer stocks are treated as state variables, with biological reproduction and growth processes constituting their equations of motion. Fire size and frequency is modeled as a stochastic event conditioned on the accumulation of fine fuels (buildup of invasive annual grass material) and stochastic ignition. Fuel stock is the third state variable with a stochastic equation of motion that determines fire size. We assume that fuel accumulation is partially controlled through fuels removal treatments, but ignition is entirely exogenous. Because pre-fire fuel treatment is more successful when cattle are restricted from grazing for a season, the model assumes a negative relationship between treatment and forage availability. In addition, in the event of wildfire the model assumes that burned land is unavailable for forage for the season. With the SDP model parameterized for a typical northern Nevada cow-calf operation, the results suggest that financial returns to a cow-calf operation are sufficiently low that reducing transactions costs alone is unlikely to induce ranchers to implement preventative land treatments.

The Conceptual Model

We model a rancher's decision problem as a discrete-time stochastic optimal control problem for an infinite planning time horizon. Let x_t denote the herd size at the beginning of year *t*, so that the herd dynamics is represented as:

(1) $$x_{t+1} = (1 + \beta)(1 - \delta)x_t - s_t,$$

where β is the net reproduction rate, δ the mortality rate, and s_t net cattle sales.[1] Without supplementary feeding during the grazing season, herd size in a given year is limited by available grazing land:

(2) $$x_t \leq \alpha A_t = f(u_t, y_t; \alpha)$$

where A_t is total grazing area available in year *t* and α is the carrying capacity of the range. A_t is influenced by land treatment level u_t because treated land is unavailable for grazing[2] and by fire size y_t. Fire size is in turn affected by fuel stock F_t and by a stochastic ignition parameter σ_t such that:

(3) $$y_t = g(F_t; \sigma_t).$$

It is further assumed that the evolution of fuel stock is governed by the following equation of motion:

(4) $F_{t+1} = h(F_t, u_t)$.

Combining (2), (3), and (4), the land availability constraint is rewritten as:

(5) $x_t \leq f(u_t, g(h(F_{t-1}, u_{t-1}); \sigma_t); \alpha)$.

The current profit is comprised of revenue from cattle sales and costs of herd maintenance and land treatment such that:

(6) $\pi_t = q(s_t) - c(x_t, u_t)$.

Finally, assuming risk-neutrality, the rancher's decision problem is represented as:

(7) $\max_{s,u} \mathrm{E}_0[\sum_{t=0}^{\infty}(1+r)^{-t}\pi_t]$, s.t. (1), (5), and (6),

where $\mathrm{E}_0[\cdot]$ is the expectation operator with the expectation formed at the beginning of the planning time horizon and r is the discount rate. Let λ^x and λ^a denote the Lagrangean multipliers associated with constraints (1) and (5), respectively, then the first-order necessary conditions for optimality are:[3]

(8) $\mathrm{E}_0\left[(1+r)^{-t}\frac{\partial q(\cdot)}{\partial s_t} - \lambda_{t+1}^x\right] \leq 0$,

(9) $\mathrm{E}_0\left[-(1+r)^{-t}\frac{\partial c(\cdot)}{\partial u_t} + \lambda_t^a\frac{\partial f(\cdot)}{\partial u_t} - \lambda_{t+1}^a\frac{\partial f(\cdot)}{\partial y_{t+1}}\frac{\partial g(\cdot)}{\partial F_{t+1}}\frac{\partial h(\cdot)}{\partial u_t}\right] \leq 0$, and

(10) $\mathrm{E}_0\left[-(1+r)^{-t}\frac{\partial c(\cdot)}{\partial x_t} - \lambda_t^x + (1+\beta)(1-\delta)\lambda_{t+1}^x - \lambda_t^a\right] = 0$, for all t.

Kuhn-Tucker conditions (8) and (9) will hold with equality when $s_t > 0$ and $u_t > 0$, respectively. Equation (10) characterizes the optimal herd size management strategy.

Condition (9) is of particular interest. The first term describes the marginal financial cost of treatment, the second term is the marginal opportunity cost of treatment through reduced rangeland availability, and the last term characterizes the marginal benefit of treatment through increased rangeland availability in the following year. Balancing costs and benefits at the margin determines the optimal treatment level for each year. Note that the second term in condition (9) will drop out whenever the current-year grazing land constraint is slack ($\lambda_t^a = 0$). When this constraint is not binding, i.e. there is sufficient grazing land for the herd, the opportunity cost of implementing treatment is lower. This implies that *ceteris paribus* treatments are more likely to be taken during a herd-expansion phase, which may occur after certain shocks (e.g. fire, drought, price shock) which cause a reduction in herd size. Note that this prediction is most relevant for cow-calf operations where herd size adjustment relies chiefly on the slow process of biological reproduction. From the third term in (9), the future benefit of treatment is larger when 1) the marginal effect of current treatment on fuel reduction $\left|\frac{\partial h(\cdot)}{\partial u_t}\right|$ is larger, 2) the marginal effect of the following year's fuel stock on fire size $\frac{\partial g(\cdot)}{\partial F_{t+1}}$ is larger, and 3) the marginal effect of the following year's fire size on range availability reduction $\left|\frac{\partial f(\cdot)}{\partial y_{t+1}}\right|$ is larger. Therefore, treatment application decisions are intricately linked with decisions on herd size adjustments and the dynamics of fuel accumulation.

Numerical Implementation

The conceptual model is numerically implemented. We apply the model to a hypothetical 5,000 acre cow-calf ranch located in northern Nevada. The model assumes the following sequence of events. The model period is one year, which starts in late summer, when wildfires are most likely to occur. We assume that only one fire can occur each year on the ranch. The model allows "emergency" herd-size adjustment if necessary after a fire in order to satisfy the grazing land availability constraint for the spring grazing season. During winter, cattle are fed with supplements; deaths occur also in winter. Next, in winter through early spring, the rancher makes the land treatment decision. In spring, births occur and the grazing season starts; 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 wildfire season.

Cattle Herd Dynamics

Equation (1) is now specified with 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:

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

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:

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

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

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

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 and Stochastic Fire

We measure fuel stock F_t in equation (4) in terms of fuel bed depth as is done in the fire science literature. We assume that, *without treatment or fire*, fuels accumulate according to a logistic growth function such that:

(14) $F_{t+1} = F_t + \rho F_t \left(1 - \frac{F_t}{K}\right)$,

where ρ denotes the intrinsic growth rate and K the carrying capacity for accumulated fuel. K is set at 1.92 feet, which is estimated to result in the largest fire that can be contained in one day (see below for fire size specification). We consider three levels of ρ for three representative rangeland conditions with respect to the prevalence of nonnative weeds, which also governs fire frequency. In condition 1, where invasion is minimal, a fire is assumed to occur on average once every 70 years. Condition 2 has more nonnative weeds, with a fire frequency of once every 20 years. Condition 3 rangeland is severely infested, with fire occurring once every 5 years. Fuels accumulate fastest in condition 3 rangelands. Accordingly, we specify ρ=0.076 (condition 1), 0.267 (condition 2), and 1.067 (condition 3).[4] We characterize fire stochasticity such that in each year fire may occur with the probabilities of 0.0143 (condition 1), 0.05 (condition 2), and 0.2 (condition 3). The probability of a fire event is considered to be independent of fuel stock; the latter is a major determinant of fire size.

Fire size, y_t, in equation (3) is defined in terms of acres burned and is specified and parameterized using information from the fire simulation model BehavePlus, which was developed from the BEHAVE fire behavior prediction and fuel modeling system (Andrews 1986; Andrews and Chase 1989; Burgan and Rothermel 1984; Andrews and Bradshaw 1990). The simulation model was run at various levels of fuel bed depth to generate the corresponding fire sizes.[5] The value of 1.92 feet for K was established by running BehavePlus with a fixed level of firefighting resources (two engines) and determining the maximum fuel accumulation whereby a fire could be contained within one day. Though larger catastrophic wildfires occur given the right conditions, they are less frequent. In this article, we do not consider these large fires and restrict the maximum fuel bed depth to be 1.92 feet. The simulation results suggest that fire size increases exponentially with fuel stock such that:

(15) $y_t = 0.0623e^{5.1551F_t}$.

In implementation, we trace the year-to-year path of *average* fuel stock across the 5,000-acres assumed as a typical ranch size. Assuming that fire and/or land treatment would reduce fuel stock to zero for the affected acreage, equation (14) is now modified to characterize $\bar{F}_t$, or average fuel stock:

(16) $\bar{F}_{t+1} = \frac{A_t}{5000}\left\{\bar{F}_t + \rho\bar{F}_t\left(1 - \frac{\bar{F}_t}{K}\right)\right\}$,

where

(17) $A_t = 5000 - \sigma_t y_t - u_t$

defines rangeland available for grazing each year. The fire stochasticity factor σ_t is 1 if a fire occurs and 0 otherwise, and u_t is acres treated for fuels removal. F_t in equation (15) should also be replaced with $\bar{F}_t$.

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. The stocking capacity in this region has been estimated between 0.001 and 0.128 cows per acre.[6] We vary the rangeland capacity parameter α within this range to investigate sensitivity of results to range productivity differences.

Revenue, Cost, and Discount Rate

Ranch revenue is derived from cattle sales. The (deterministic) 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. Cow purchases are also discouraged by specifying a high premium (tenfold) over cull-cow price.

Based on University of Nevada Cooperative Extension enterprise budget estimates, we specify an average winter feeding cost of \$145 per animal unit. Additional herd maintenance costs are applied to animals that survive the winter. Using the same enterprise budget estimates, a linear herd maintenance cost curve is estimated ($31.752 + 0.1354AU_t$; in \$000, AU_t is animal units). We systematically vary per-acre fuels treatment costs in the following exercises to evaluate effects of policies that might be offered (such as cost sharing) to induce rancher efforts to contain invasive grasses. Actual fuel/invasive weed treatment costs and rates of efficacy depend on methods used. We use a low-cost method of \$20 per acre (herbicide application) as a benchmark. We set the discount rate *r* at 10%.

Solution Technique

We assume the rancher uses updated information about herd size and the fuel stock to make management decisions each year, and problem (7) is solved using a SDP solution technique. The resulting Bellman equation is:

(18) $V(x_t;\sigma_t) = \max_{s,u}\{\pi_t + (1+r)^{-1}\mathrm{E}_t[V(x_{t+1};\sigma_{t+1})]\}$, s.t. (1), (5), and (6).

In numerical implementation, we use a value function approximation approach, where the unknown value function $V(\cdot)$ is approximated with a polynomial and then the problem (18) is solved forward in time to obtain *s* and *u* for each time period (Judd 1998; Miranda and Fackler 2002), following the steps outlined in Kobayashi et al. (2007). Once an approximated value function is obtained, we solve the problem using a simulated time-series for fire events, randomly generated according to corresponding fire frequency assumptions (every 5, 20, and 70 years). The model is implemented for 100 years.

Model Results

With the default treatment cost of $20 per acre and under the other default parameters, the model finds that it is not optimal to invest in land treatments. In this case, fuel stock dynamics are entirely driven by fire occurrences (Figure 1). Under a randomly-generated fire sequence for a condition 1 scenario, fire occurs in years 27 and 41. As the fuel stock is sufficiently low in these two years, the resulting fires are small (4.64 acres in year 27 and 58.58 acres in year 41). As a result, fuel accumulates steadily, without major disruptions, towards the carrying capacity of 1.92 feet. Under condition 2, fire occurs in years 1, 7, 27, 38, 41, 68, 85, and 93. Increases in accumulated fuels increase fire size (850-1,240 acres) and clearly affect fuel dynamics. Similar patterns are observed under condition 3, but with fire occurring much more frequently.

The corresponding cow-stock dynamics are depicted in Figure 2. The optimal strategy is to maintain a stable number of cattle while letting random fires periodically drop herd size. In a year with a sufficiently large fire, the land availability constraint binds so that adjustment sales of heifers and cows must occur, causing the sharp drops in the cow stock shown in Figure 2. Later in the same year, heifer-calf sales are reduced to allow rebuilding of the herd for the following year. Note that, in this model, immediate recovery of herd size is attained through retaining all heifer calves after a fire. In reality, however, a rancher may face a borrowing constraint so that a certain level of revenue must be raised to finance operating costs each year. In this case, zero heifer-calf sales would not be an admissible option, and the effects of a fire on herd size would be prolonged. While optimal equilibrium herd size is somewhat affected by fire frequency, range productivity appears to be its major determinant. When the rangeland carrying capacity is reduced by half from the default 0.128 head per acre, the equilibrium cow stock is reduced from about 370 to 190 head (Figure 2).

As seen in Figure 2, the optimal cow stock fluctuates every year, as does annual profit. Variations of annual profits are driven by herd-size adjustments. In a year with fire, revenue is lower due to reduced calf sales. However, with reduced feeding cost and herd maintenance cost, in balance, profit reduction in fire years is relatively small. On the other hand, in the year after a fire, the calf crop is smaller due to the reduced breeding stock in the previous year, which results in lower calf sales. As one would expect, there is a sharp drop in profit in the year after a fire.

Table 1 summarizes means and standard deviations for herd size and profit for the 3 rangeland conditions.[7] Results for conditions 1 and 2 are similar: average cow stocks are 369 (condition 1) and 366 (condition 2) head, while average annual profit is $25,349 (condition 1) and $24,419 (condition 2). With increased fire frequency from condition 1 to 2, annual variation of these outputs increases. Under condition 2, the standard deviation of the cattle stock is 31% higher and that of annual profit 12% higher than under condition 1. On the other hand, the average cow stock and annual profit under condition 3 are reduced by 5% and 19% relative to condition 1. Variability substantially increases under condition 3: relative to condition 1, the standard deviation under condition 3 is higher by 102% for cow stock and by 28% for annual profit. Moreover, the discounted sum of profits (NPV) over the 100 years is 19% lower under condition 3 than under condition 1.

Although treatment is optimally not adopted at $20 per acre of treatment cost, the model indicates that the rancher recognizes the benefit of treatment in reducing fuel stock and fire size. In fact, if treatments are available at no cost, the model predicts that the rancher operating on a condition 3 rangeland adopts it every year, on average, for 656 acres annually (results not shown). This indicates that the opportunity cost of treatment (second term in (9)) is sufficiently small relative to the future benefit (third term). With this intensive treatment strategy, the rancher achieves NPV of $145,598, which is comparable to the NPV under condition 2 without any treatment (see Table 1).

Figure 3 depicts the optimal treatment strategy under condition 3 when treatment cost is $0.25 per acre. This is nearly the highest treatment-cost level for a rancher to ever adopt treatment, as the model is currently specified.[8] As predicted by the first-order condition (9), treatments are taken when herd size drops, i.e. at the beginning of the herd expansion phase, and the land constraint becomes slack. The optimal timing of treatment also coincides with a reduction in fuel stock. This is consistent with condition (9) combined with the specification of the relationship between treatment and fuel accumulation in equations (16) and (17). Given this specification, the marginal effect of treatment on fuel reduction $\left|\frac{\partial h(\cdot)}{\partial u_t}\right|$ is decreasing in $\bar{F}_t$, suggesting that earlier treatment is more effective than treating later when fuel stocks are higher. In all, these results suggest that policies intended to affect ranchers' incentives to implement land treatment need to take into consideration factors that are specific to cow-calf operations such as cattle cycle, fire, and other shocks, as well as the dynamics of range ecology.

Summary and Conclusions

In this article, a numerical dynamic model is developed to characterize the decision problem of a rancher operating on rangelands in northern Nevada that are affected by invasive annual grasses and wildfire. The model incorporates decisions about herd size management of a cow-calf operation and fuels treatment to reduce the size of rangeland wildfires. Currently, high transactions costs to obtain permits to implement land treatments on federally-owned rangeland appear to limit rancher involvement. The results of the model suggest that ranch income motives alone are likely insufficient for private ranchers to adopt preventative land treatments. The current treatment cost ($20 per acre at the minimum) appears to be prohibitively expensive relative to the benefits derived from the treatments under the low-productivity, semi-arid rangeland conditions.

However, the model developed in this article omits certain outcomes of preventative land treatments. First, for simplicity the present model assumes a one-year grazing suspension on rangelands affected by fire, whereas in reality grazing is not allowed for two years after a fire, possibly three, depending on rangeland condition. Accordingly, the current specification underestimates the opportunity cost of fire or the benefit of treatment. Second, the model does not include inter-temporal externalities that occur when rangeland conditions degrade with continued expansion of invasive annual weeds and increased wildfire frequency and size. Rangeland conditions (1, 2 and 3) were exogenously imposed in this model. In reality, more productive and minimally weed-infested condition 1 rangelands can be converted into condition 2 rangelands, characterized by more weeds, lower stocking capacities, and more frequent and larger wildfires. According to rangeland ecologists, this conversion is a function of the stocking rate after fires and prevalence of invasive weeds. Condition 2 rangelands may then, possibly irreversibly, convert to condition 3, unless treatments are implemented or some other measures are taken. As seen in Table 1, under condition 3, profitability is lower and its variability is higher than under "healthier" range conditions. The transition between these conditions can be incorporated into a future version of this model by imposing probabilities of conversion. We expect that this would increase the cost of invasive weeds and wildfires, and increase the marginal value of treatment.

Third, a related issue not addressed in the model is the property value of the private portion of a ranch that may decline with declined rangeland condition, whether the public or private portion. In addition, financial liquidity needs can be accommodated with an added constraint. This would further slow herd growth after fire. We expect these modifications also to result in increased value of treatment.

At the same time, it is not clear which types of costs ranchers actually internalize. A survey of ranchers operating in this region will be useful to empirically investigate how ranchers' knowledge about rangeland ecology and perceived effects of land treatments relates to their actual behavior. Ranchers may not be aware of the ecological processes that cause transitions between rangeland conditions. If they are not aware of this, then the private level of treatment is below what is financially optimal. Finally, treatments that reduce invasive weeds and severity of wildfires preserve other rangeland values that accrue to society. These include water quality, reduced wind and water erosion, wildlife habitat, recreation, and other non-market benefits. As a result, it is very likely that the private optimal level of rangeland treatment is lower than what is optimal for the society. Given that the ranchers already have some incentive, efficient policies to induce socially optimal levels of invasive weed treatment may include enhancing private incentives through programs such as cost sharing.

Footnotes

[1] For presentation simplicity, animals of different age/sex classes are not differentiated in the conceptual model. This and other details of cattle herd dynamics are addressed in the numerical model.

[2] Depending on treatment methods, treated areas may be unavailable for grazing for an extended period for the treatment to be effective. For simplicity, we assume a treated area is unavailable for the year of treatment.

[3] Similar derivations are made in Hamilton and Kastens (2000).

[4] The parameters are determined so that the fuel bed depth reaches 1 foot, which is a common benchmark for the fuel type in the region, in 70 (condition 1), 20 (condition 2), and 5 (condition 3) years according to the logistic growth curve.

[5] "Contain area" generated in BehavePlus is used as a proxy for y_t, the area that becomes unavailable for grazing due to the fire.

[6] 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.

[7] For each range condition, 100 random fire time-series are generated. The results presented in the table are averages of the 100 simulations.

[8] At this cost level, treatment is adopted in only one year under condition 2 and never under condition 1.

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Table 1. Summary Results of Cow Stock, Annual Profit, and NPV

		Cond'n 1	Cond'n 2	Cond'n 3
Cow Stock	Average (average of 100 years)	369.35	366.39	352.43
	Standard deviation (annual variation)	13.66	17.95	27.54
Annual Profit	Average (average of 100 years)	$25,349	$24,419	$20,562
	Standard deviation (annual variation)	$9,381	$10,481	$12,014
NPV of Operation	Discounted sum (over 100 years)	$148,591	$146,937	$120,372

Note:
Results shown are averages over 100 simulations.

Figure 1. Optimal Fuel Stock Dynamics
(Treatment cost = $20/acre)

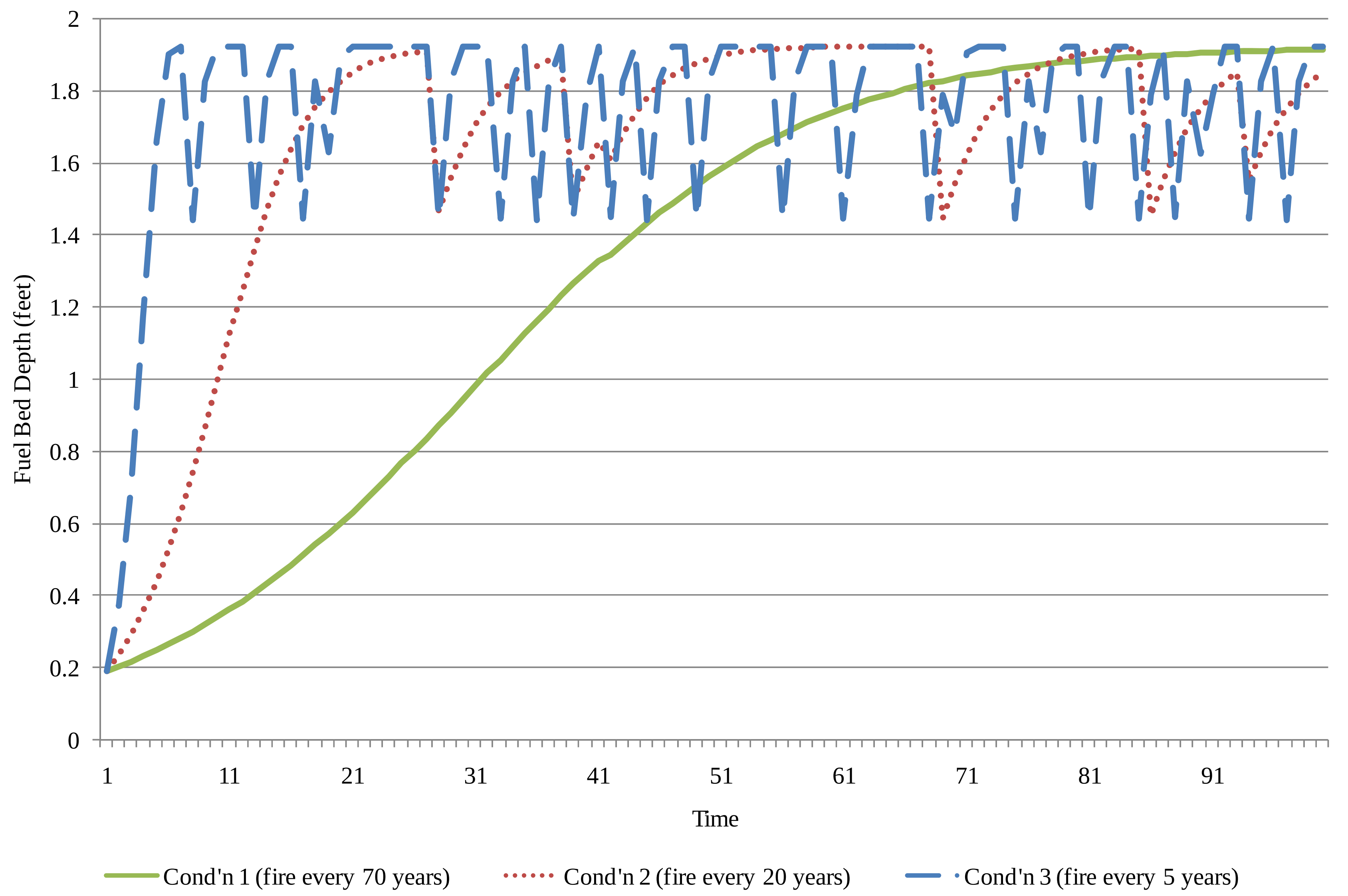
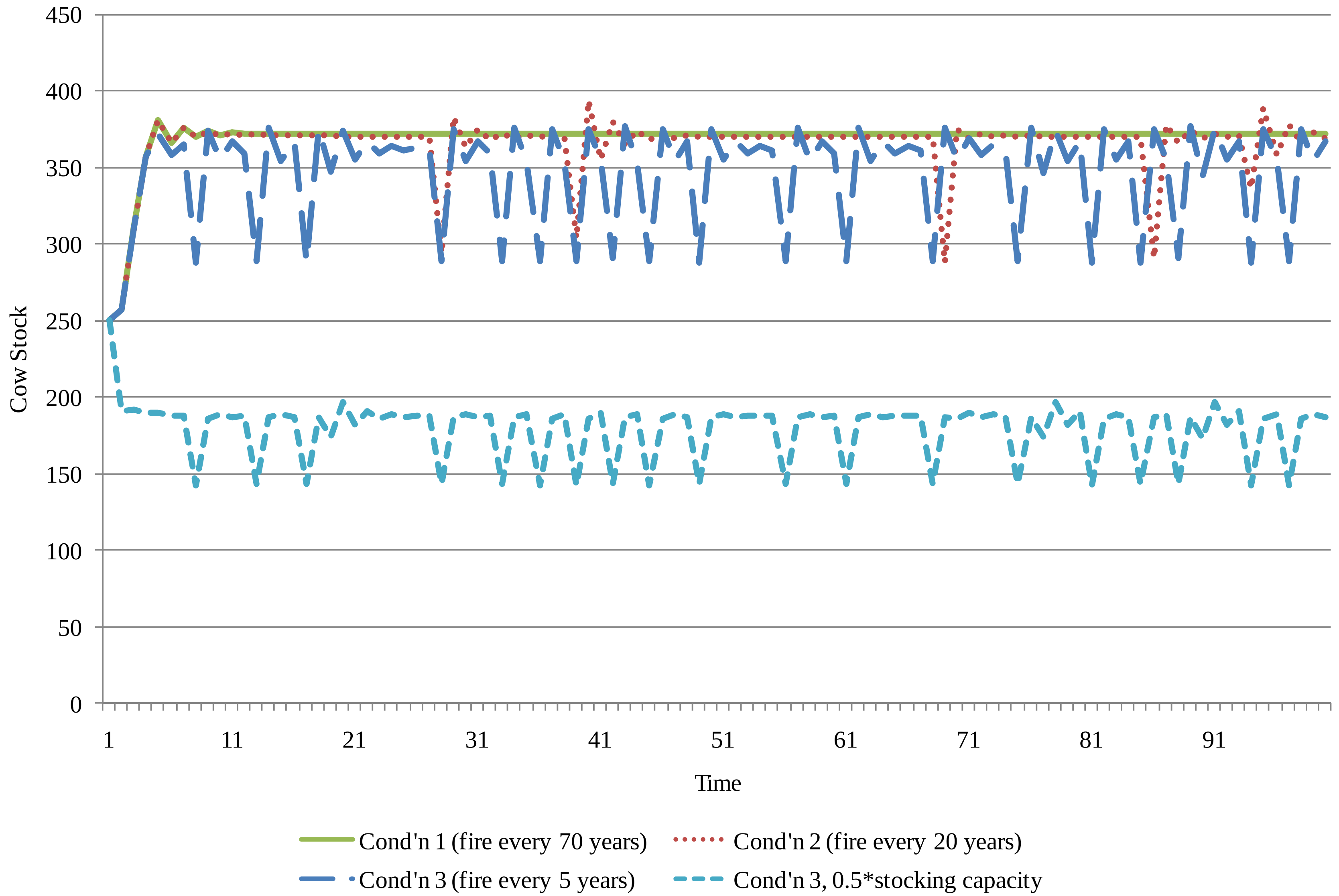


Figure 2. Optimal Cow Stock Dynamics
(Treatment cost = $20/acre)



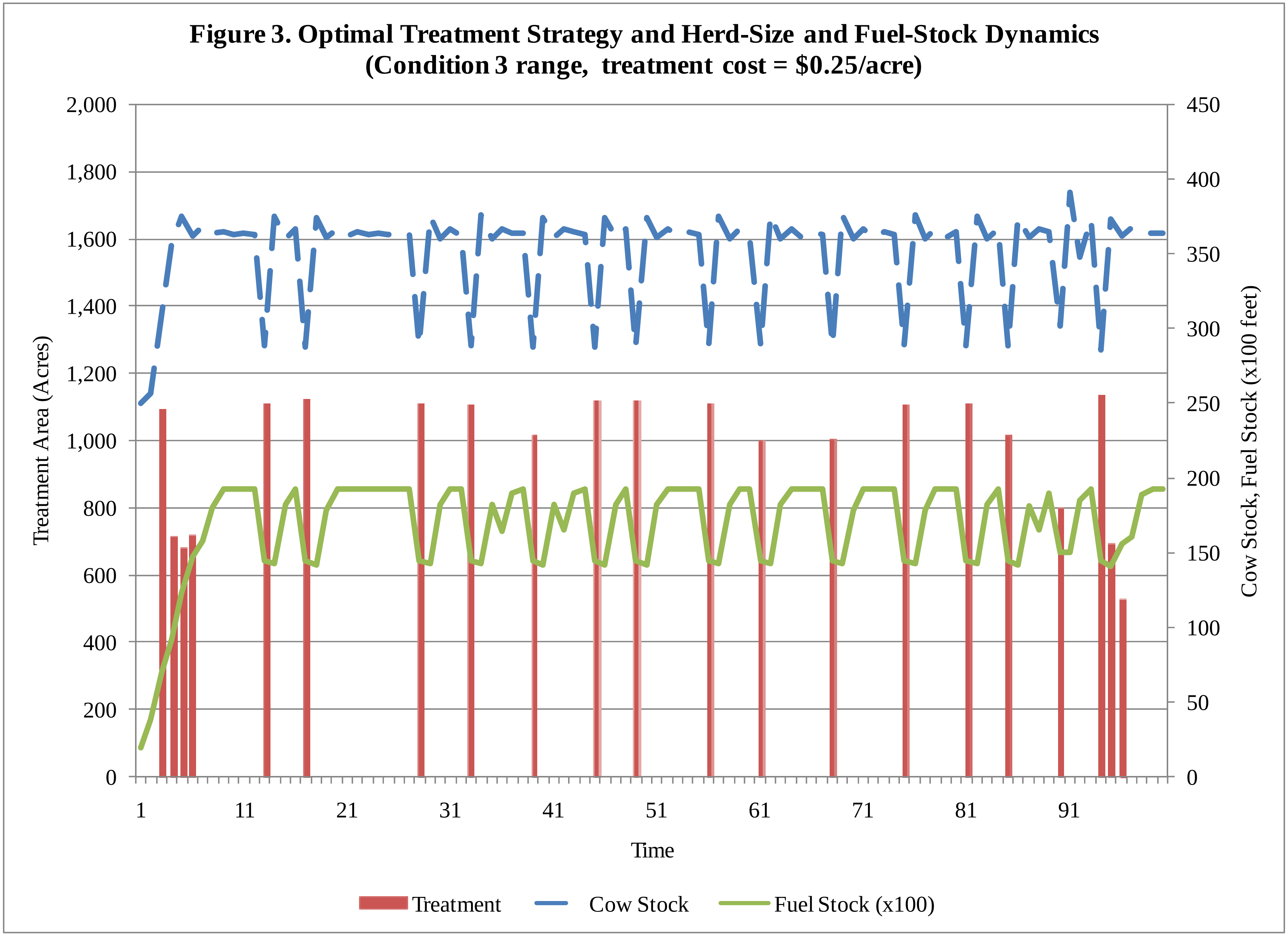


Figure 3. Optimal Treatment Strategy and Herd-Size and Fuel-Stock Dynamics
(Condition 3 range, treatment cost = $0.25/acre)
Treatment Area (Acres)
2,000
1,800
1,600
1,400
1,200
1,000
800
600
400
200
0
Cow Stock, Fuel Stock (x100 feet)
450
400
350
300
250
200
150
100
50
0
1
11
21
31
41
51
61
71
81
91
Time
Treatment
Cow Stock
Fuel Stock (x100)