Optimal Control of Wild Horse
Populations with Nonlethal Methods

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1. Introduction

Wildlife populations provide a variety of amenities to society, ranging from food and recreation to ecosystem regulation and existence values. Wildlife populations also can impose costs on society through interference with human activities, degradation of habitat, and spreading of disease. Striking a balance between the costs and benefits of wildlife often involves active population management. Direct population control is most commonly carried out through increased regulated hunting or trapping[1] (Rondeau, 2001). However, when species are endeared to the public, lethal population control methods may not be palatable from a societal perspective. In these cases, wildlife is usually captured then relocated, or captured then held in captivity. A third alternative, fertility-control, is an emerging non-lethal population control method that can be implemented without displacing animals from their range.

This study evaluates alternative nonlethal strategies for controlling wild horse populations in the American West--an animal for which traditional population control methods are not a desirable option. Dynamic economic models of optimal wild horse management are developed for two non-lethal management methods: horse removals and fertility control. A third "hybrid" model is also developed to investigate the effectiveness of using removals and fertility control in tandem. The models incorporate the costs of on-range management, the costs of off-range holding, and the net-benefits associated with wild horse populations. Model parameters are calibrated using published studies on wild horse population biology and Bureau of Land Management (BLM) expenditure data. The value of ongoing status quo management is estimated, and policy simulations are generated for horse removal, fertility control, and hybrid management scenarios. Additional scenarios are developed to assess the sensitivity of model results to specified parameter values.

The simulation results are evaluated to glean insights for effectively managing wild horse populations.

2. Background

Free roaming horses are an enduring icon of the American West, but an effective and sustainable population management plan has eluded land managers for decades. Western wild horse populations are descendants of domestic animals that were introduced by Spanish explorers in the early 1500s. Once introduced, the horse populations grew quickly, and by the year 1800 wild horses roamed in large herds from Texas to California (Dobie, 1952).

Rapid settlement of the western United States and the subsequent development of western lands led to conflicts with wild horse populations in the 1800s and 1900s. During this time, wild horses were sought out and destroyed or captured for commercial slaughter to prevent their interference with grazing and agricultural activities (Phillips, 2012). By 1971, the total U.S. wild horse population was reduced to approximately 9,500 a (Pitt, 1984). Some wild horse advocates viewed these management practices as inhumane, and by the mid-20th century advocates had organized to lobby Congress for wild horse protection. The campaign garnered public interest and media coverage; and in 1959 Congress passed legislation to prohibit the use of aircraft or motorized vehicles to hunt horses and burros on public lands (Pitt, 1984).

In 1971 Congress passed legislation that continues to guide BLM's management of wild horse populations. The Wild and Free-Roaming Horses and Burros Act of 1971 banned private horse gathers and tasked the BLM with "protection, management and control of wild free-roaming horses and burros on public lands" (NRC, 2013). The bill's language also guides BLM to manage horses and burros at "the minimal feasible level[2]" to "achieve and maintain a thriving natural

ecological balance on the public lands" (NRC, 2013). These directives must be balanced with the BLM's mandate to manage public lands for multiple uses. Without active control, horse populations can become a stress on grazing land (Pimentel, Zuniga, & Morrison, 2005). To prevent rangeland degradation, BLM actively gathers wild horses and removes them from the range with the goal of keeping populations within predetermined appropriate management level (AML) ranges. Adoptive homes are sought for removed horses and unadopted animals are sent to long-term holding facilities. Current BLM policy does not support selling unwanted horses for slaughter[3].

In recent years, unwanted horses have been accumulating at holding facilities. During the 2015 fiscal year, 66% of the Wild Horse and Burro Program's (WHBP) $77.2 million budget was dedicated to maintaining captive horses (BLM, 2016b). In 2000, by comparison, holding accounted for 46% the $19.8 million total program budget (GAO, 2008). Furthermore, Garrott and Oli (2013) estimated that the total net present value (NPV) cost of caring for the horses currently in holding, if no more were added, at nearly $350 million. Under the existing management program, Garrott and Oli estimate the total 2013-2030 costs of maintaining unadopted horses in captivity would total $1.1 billion.

Facing an uncertain future, BLM requested that the National Research Council (NRC) scientifically evaluate the challenges facing the WHBP (NRC, 2013). In their report, the Council offered guidance for developing dynamic models to assist BLM with identifying cost-effective management options. Specifically, a need was expressed for a model that evaluates the dynamics of on-range and off-range populations, and the costs and consequences of existing and alternative management regimes (NRC, 2013).

3. Models of Optimal Wild Horse Population Control

This section presents dynamic models of optimal horse population control for two management methods: removing horses from the range and treating horses with a fertility control vaccine. A hybrid management regime combining removals with fertility control is then developed. The optimal management policy under a given set of assumptions is to choose a sequence of annual population control efforts that maximizes the net benefits associated with wild horse populations over time.

Both removal and fertility control methods require that horses be gathered on the range. With removal, gathered horses are transported to short-term facilities where adoptive homes are sought for the animals. Horses that go unadopted are shipped to long-term holding facilities. One of the most promising, appropriate, and practical fertility control methods in wild horse populations is the long-lasting formulation of Porcine Zona Pellucida (PZP-22)[4], an imunocontraceptive that is administered through injection after horses are gathered. Treated horses are released back to the range where the contraceptive remains about 85% effective after 22 months (NRC, 2013).

The annual cycle of horse management in the optimization models coincides with the fiscal year. Management actions begin October 1 and continue through February[5]. Wild horse foaling (i.e. births) occurs from March 1 to June 30, and BLM prohibits helicopter gathers during that period (BLM, 2010). Net population benefits are assumed to accrue from July 1 through September 30.

Optimal Horse Removal

The net present value of a population of wild horses managed in perpetuity with removal methods is maximized where the chosen sequence of removals $\{Y_0, \dots, Y_\infty\}$ solves the problem in [1].

$$\max_{\{Y_t\}} \sum_{t=0}^{\infty} \rho^t \left[B(X_t) - C^g(Y_t) - C^a(ADPT_t) - C^{ur}(Y_t) - C^{ub}\left(Y_t \frac{F(X_{t-1})}{X_{t-1}}\right) - SC_t \right] \quad [1]$$

Subject to:

$$X_t - X_{t-1} = F(X_{t-1}) - Y_t[1 + \frac{F(X_{t-1})}{X_{t-1}}]$$

$$Y_t \leq \min(Y^{max}, \delta X_{t-1}) \; \forall \; t$$

X_{-1} is given

$$X_t^{min} \geq AML \; \forall \; t$$

$$SC_t = \begin{cases} 0 \; if \; Y_t = 0 \\ s \; if \; Y_t > 0 \end{cases}$$

$$ADPT_t = \begin{cases} Y_t[1 + \dfrac{F(X_{t-1})}{X_{t-1}}] & if \; Y_t[1 + \dfrac{F(X_{t-1})}{X_{t-1}}] \leq \gamma_t \\[2mm] \gamma_t & if \; Y_t\left[1 + \dfrac{F(X_{t-1})}{X_{t-1}}\right] > \gamma_t \end{cases}$$

Initial population X_{-1} is the population size when the first management cycle begins. The choice variable Y_t is the number of horses gathered during the first five months of period t. In the absence of management, the horse population grows by $F(X_{t-1})$ during period t foaling. Under optimal removal management, the population transitions to size $(X_{t-1} - Y_t)$ after removals are implemented and then grows to size X_t before benefits are realized in the latter part of period t. Many of female horses removed from the range are pregnant and give birth off-range rather than on-range. Thus the effective impact of removals on horse population growth is assumed to be $Y_t[1 + \frac{F(X_{t-1})}{X_{t-1}}]$, where $\frac{F(X_{t-1})}{X_{t-1}}$ approximates the per-capita growth increment for horses in a population of size X_{t-1}. This also implies that removing Y_t horses from the range results in $Y_t \frac{F(X_{t-1})}{X_{t-1}}$ captive horse births during period t.

The parameter γ_t represents adoption demand in period t. The first γ_t removed and captive-born horses are adopted and the rest go to long-term holding facilities. Thus, the number of horses adopted in period t $(ADPT_t)$ equals $Y_t[1 + \frac{F(X_{t-1})}{X_{t-1}}]$ if effective removals (i.e. removed plus captive-born horses) are less than or equal to γ_t, and equals γ_t otherwise. The total number of horses from period t managment that are not adopted equals $Y_t[1 + \frac{F(X_{t-1})}{X_{t-1}}] - ADPT_t$.

The total cost of gathering horses $C^g(Y_t)$ depends on the number of horses gathered. Initiating management actions at the beginning of a management period is associated with setup costs $SC_t = q$. The costs associated with adopted horses (C^a) are assumed to be a function the number of horses adopted $ADPT_t$. Likewise, the costs associated with unadopted removed horses (C^{ur}) and unadopted captive-born horses (C^{ub}) are functions of the number of removed and captive-born horses, respectively.

Wild horses are associated with economic values beyond the costs of population management. Wild horses provide recreation benefits for wildlife viewers and non-use benefits for individuals who are made better by knowing that wild horses roam free on the western range. Horse populations can also impose economic costs through displacement of wildlife species and domestic livestock, and through degradation of rangelands. The net economic benefits (total benefits minus total costs) provided by a wild horse population of size X_t are given by the function $B(X_t)$. It is assumed that $B(X_t)$ is a strictly concave, single-peaked function that reaches its maximum where $X = \bar{X}$. Thus, the marginal benefits function $B_x > 0$ for $X \in [0, \bar{X})$ and $B_x < 0$ for $X \in (\bar{X}, \infty]$.

A number of constraints are placed on the optimal horse management solution. During a given period, the horse population is smallest after removals occur but before foaling begins. The models specify that this minimum population level, X_t^{min}, must be above the low range AML set by BLM.

Wild horse managers may be constrained by the number and proportion of animals that can be gathered in a given year (NRC 2013). Constraint parameter δ is the maximum proportion of the pre-gather population that can be gathered in a single period. Gathers are also constrained in the model by the maximum total number of horses that can be gathered in a single period, Y_{max}. Finally, the discount factor ρ reflects time preference and is bound between 0 and 1 (inclusive).

Optimal Fertility Control

The optimal fertility-control program is a sequence of fertility treatment choices that maximizes the problem:

$$\max_{\{Y_t\}} \sum_{t=0,2,4,\ldots}^{\infty} \rho^t [B(X_t) + \rho B(X_{t+1}) - C^g(Y_t) - C^{fc}(Y_t, HMA) - SC_t] \qquad [2]$$

Subject to:

$$X_{t+2} - X_t = F_{t+1}(X_t, Y_t) + F_{t+2}(X_{t+1}, Y_t)$$

$$Y_t \leq \min(Y^{max}, \delta \tilde{X}_t)$$

$$X_{-1} \text{ is given}$$

$$\tilde{X}_t \geq AML \; \forall \, t$$

$$SC_t = \begin{cases} 0 \; if \; Y_t = 0 \\ q \; if \; Y_t > 0 \end{cases}$$

As in the removals model, the horse population is of size X_{-1} when fertility control management commences and Y_t horses are gathered during the first five months of period t. All gathered horses are released back to the range after the mares (i.e. female horses) are treated with contraceptives. Gathers are assumed to occur once every two periods to coincide with the approximate effectiveness duration of the fertility control formulation currently used by BLM (i.e. PZP-22) [6].

Fertility control treatments prevent conception but do not interfere with the development of horses in utero (Kirkpatrick & Turner, 2003). Thus, fertility treatments applied in period t begin to impact population growth in period $t + 1$. Because of this delayed impact, the population grows to size $X_0 = F(X_{-1}) + X_{-1}$ by the beginning of the second period regardless of the initial level of fertility control effort. The fertility control formulation considered in this model is effective for two periods, so the treatments applied in period t impact population growth in periods $t + 1$ and $t + 2$. Fertility control treatments directly impact population growth rate. The population growth increments impacted by fertility control in period t are given by $F_{t+1}(X_t, Y_t)$ and $F_{t+2}(X_{t+1}, Y_t)$.

Costs specific to fertility-control management (C^{fc}) are assumed to be a function of the number of horses gathered for treatment (Y_t) and the number of BLM herd management areas (HMA) where fertility control is undertaken[7]. Gather constraints under fertility control management mirror the constraints under removals with one notable exception. The delayed effect of fertility control necessitates a more restrictive gather constraint to facilitate dynamic programming of the solution. The constraint $\tilde{X}_{t-1}$, is the lower bound of the previous period population[8].

Hybrid Management: Combining removals and fertility control

Horse removal and fertility methods have thus far been considered independently. Each of these approaches has advantages that could be leveraged in a population management regime utilizing both removals and fertility control. The following section discusses the strengths and weaknesses of removals and fertility control and proposes a hybrid management regime that combines both methods.

Compared to removals, fertility control is a more benign method of population management that better aligns with BLMS's mandate to manage horses at the "minimum feasible level". Fertility control may also represent a low cost population control alternative as it does not require off-range management of horses. However, reducing or stabilizing horse populations with fertility control alone requires that a large share of the population be frequently gathered and treated (NRC, 2013).

Removal management directly decreases the base from which a population grows and prevents removed pregnant females from giving birth on the range. Furthermore, removals have an immediate impact on the population compared to the delayed effect of fertility control. These characteristics make removal management a more effective means of reducing horse populations[9]. Management with removals also has drawbacks. It requires costly long-term management of off-range horses and is a more intensive management alternative compared to fertility control.

Because removals and fertility each have respective strengths and weaknesses, a management alternative that allows for both removals and fertility control may be preferred to management under a single method. Specifically, a "hybrid" management program could allow for population reductions while reducing the costs of maintaining populations at a desirable level. Hybrid management may also reduce the intensity of population management subject to maintaining ecological balance on the range.

The National Research Council's report describes a hybrid management scenario where populations are managed within their current AML range (NRC, 2013). Following this description, the Hybrid scenario is specified to involve several years of intensive removals to reduce the population, followed by an effort to manage the population with fertility control. Specifically,

hybrid management involves consecutive years of removals at the $Y_t = \min(Y^{max}, \delta \tilde{X}_t)$ level until the population is within the AML range[10]. Following the initial reduction phase, horses are managed on a two-year gather cycle with fixed removals and optimally chosen fertility control effort. The Hybrid management model is in presented in Appendix A1. The fixed number of horses removed at the beginning of each management cycle (q) is the minimum removal effort that maintains population below the carrying capacity throughout the optimal management cycle.

4. Model Calibration

This section specifies functional forms, parameters, and assumptions for the optimal horse management models. Separate models were developed for Nevada and Oregon based on data availability. The biological parameters specified in the models are based primarily on studies of the Beatys Butte herd management area (HMA) in eastern Oregon[11]. Monetary costs and benefits in the models are inflation-adjusted to 2015 dollars. The discount factor (ρ) reflects a 4% discount rate in the Base model[12].

Wild Horse Gather Costs

The annual cost of conducting horse gathers depends on the number of horses gathered. State-level gather expenditure data were obtained from BLM for fiscal years 2009 through 2015 to parameterize this relationship. The gather expenditure data were escalated to the 2015 fiscal year[13] and then merged with gather statistics from the WHBP website (BLM, 2016a). Linear models regressing the gather expenditure data on the number of horses gathered were estimated for two candidate specifications: a linear specification to represent constant marginal gather costs, and a quadratic specification to represent increasing marginal costs. The quadratic specification provides a superior model fit for the Nevada data and the linear specification provides a better fit for Oregon

data, according to the adjusted R^2 values of the candidate models. The final Oregon and Nevada fitted models explain 75% and 87% of the variation in annual gather costs, respectively, according to the final model R^2 values. The model constants are estimates of gather setup costs (s) and the model coefficients are marginal gather cost estimates. Setting up gather operations is estimated to cost approximately $45,000 Nevada and $155,000 in Oregon. The marginal cost of gathers in Oregon is constant at $490 per horse. In Nevada, marginal gather costs are increasing. The cost of gathering the first horse is $345 and the marginal cost of gathering the five thousandth horse is $1,078. Other potential determinants of state-level gather costs were investigated by sequentially including additional covariates in the regressions described above[14]. However, none of the candidate covariates improved model fit according to the adjusted R^2, suggesting that gather costs are best predicted by the number of horses gathered without additional covariates.

The gather constraint parameters are specified as follows. The maximum number of horses that can be gathered in a given period (Y_{max}) is set as the maximum number gathered in a single fiscal year in Oregon ($Y_{max} = 1,290$) from 2009-2015. In Nevada, where the current population is a greater share of the AML, the constraint is set to equal 125% of the maximum number gathered in a single fiscal year in Nevada from 2009-2015 ($Y_{max} = 7,165$). Further, no more than half of the pre-gather population can be removed in a single period ($\delta = .5$).

Off-range Management Costs

Horses removed from the range are transported to short-term holding corrals where they remain until they are adopted or transported to long-term pastures. Captive-born horses are foaled during the spring of the same period in which their mothers are gathered. Under current BLM policies, managers assume responsibility for the life-time care of each removed or captive-born horse that is not placed with private owners. The optimization model reflects this by specifying off-range

management costs as the present value life-time costs of caring for horses removed in a given period.

Off-range holding costs are a function of the duration horses spend in holding facilities. The short-term holding duration depends largely on adoption demand and the capacity of long-term holding facilities to accept new animals[15]. The models assume that future annual adoption demand remains constant at the 2010-2014 average (i.e. $\gamma_t = \gamma \; \forall \; t$) and that long term holding capacity is not limiting. The model further assumes that that adopted horses spend an average of 200 days in short-term holding[16] and that equal proportions of removed and captive-born horses are adopted in a given management cycle. The length of time unadopted horses spend in long-term holding depends on the age of horses entering long term facilities and their life expectancy. Garrott and Oli (2013) found that the average age of horses entering long-term holding was seven years, and that these horses typically lived an additional 15 years[17]. We adopt these estimates by assuming that removed horses entering long-term holding average seven years of age and that horses typically live to be 23 years in long-term facilities. The holding assumptions for unadopted horses are as follows. Removed unadopted horses spend two years in short-term holding, and captive-born unadopted horses spend three years in short-term holding, before they are shipped to long-term facilities. Removed unadopted horses live an average of 15 years in long-term holding while captive-born unadopted live in long-term holding for 19 years on average.

Off-range management costs were parameterized with WHBP adoption, horse holding, and expenditure data. Per-hose adoption expenditures averaged $2,707 annually from FY 2011-2015 and adopters of wild hoses paid a $125 fee. Annual adoption demand in Nevada and Oregon averaged 75 and 196 horses, respectively, from FY 2011-2014 (i.e. $\gamma^{OR} = 196 \; and \; \gamma^{NV} = 75$). From FY 2011-2015, long-term holding expenditures averaged $1.52 per day and short-term

holding expenditures averaged \$5.37 per day[18]. The cost of shipping unadopted horses to long-term facilities is \$3.29/mi/40 horses (Arneson, Beutler, & Hurst, 2002) and the average distance from short-term facilities to long-term facilities is 1,500 miles[19]. Horses removed from the range are associated with miscellaneous costs related to compliance inspections, horse preparation, and additional holding. Total miscellaneous costs are \$210 for adopted horses and \$726 for unadopted horses[20].

Combining the horse holding duration assumptions with the specified unit cost parameters yields present value total costs estimates for management of adopted horses (C^a), removed-unadopted horses (C^{ur}), and captive-born unadopted horses (C^{ub}). Constant marginal off-range management costs are assumed for each of these cost categories. The present value total cost of off-range management for adopted horses is \$3,866 per animal (67% adoption, 28% short-term holding, 5% miscellaneous). The present value total cost of off-range management for removed unadopted horses is \$10,547 per animal (56% long-term holding, 36% short-term holding, 7% miscellaneous, 1% shipping), and \$12,962 per animal for captive-born unadopted horses (51% long-term holding, 43% short-term holding, 6% miscellaneous, 1% shipping).

Wild Horse Population Biology

Eberhardt and Breiwick (2012) examined growth data from four wild horse populations, including one in the western United States. They found that the populations grew according to a theta logistic growth function with the parameter controlling the inflection point equal to two, as shown in equation 4.3. The carrying capacity (K) is the maximum population that can be sustained by an environment given available resources, and the internal rate of growth (r) is equal to ($b - m$), the birth rate minus the mortality rate.

$$F(X_{t-1}) = X_{t-1} r \left[1 - \left(\frac{X_{t-1}}{K} \right)^2 \right] \qquad [3]$$

The theta logistic growth function exhibits properties that add intuition to the equation. The term $X_{t-1} r$ represents the internal increment of growth of the population and $X_{t-1} r \left(\frac{X_{t-1}}{K} \right)^2$ captures the density-dependent population effects. As carrying capacity K goes to infinity, the population is unconstrained by density effects, and population growth is equal to the internal increment of growth. As the stock approaches the carrying capacity, growth goes to zero.

For the Beatys Butte herd in eastern Oregon, Eberhardt and Breiwick (2012) estimated an intrinsic growth rate (r) of 0.28 and a carrying capacity of 1,202 horses. The models developed in this study assume that in the absence of management, state horse populations grow according to equation [3] with $r = 0.28$. The states are assumed to have the same carrying capacity to high-bound AML ratio as the Beatys Butte herd.

The models specify the initial population size based on BLM's population estimates from March 1, 2015. Because the models use population estimates from the beginning of the fiscal year, the BLM population estimates are assumed to grow under model assumptions without management. In the the optimization models, $X_{-1} = F(X_{BLM}) + X_{BLM}$, where X_{BLM} is the 2015 BLM estimate and X_{-1} is the population at the start of management.

The Effect of Fertility Control on Wild Horse Population Growth

The relationship between horse population growth and fertility control effort and is specified next[21]. Recall that Eberhardt and Breiwick (2012) estimated the internal rate of growth for the Beatys Butte herd at $r = 0.28$ without managment. Another study of the Beatys Butte herd (Eberhardt, Majorowicz, & Wilcox, 1982) estimated the average annual survival rate at 0.926, implying a mortality rate (m) of 0.074. Thus, the internal rate of growth at Beaty's butte equals

0.28 with no fertility control, and equals -0.074 when every female in the herd receives effective contraception. In reality, PZP-22 is not 100% effective at preventing horse pregnancy. Bartholow (2007) reports that PZP-22 was 94% effective in the first year after treatment and 82% effective in the second year for Nevada's Clan Alpine herd[22].

To maintain tractability, the optimal fertility control model assumes an equal sex ratio in horse populations, homogeneity across gender-specific gather production, and no gender selectivity in gathers. These assumptions yeild the simplifying condition that half of the horses gathered for fertility suppression purposes are treated with fertility control agents and the other half are returned to the range.

The intrinsic rate of growth without management is $r_0 = 0.28$. Contraceptive applications occur on a biannual cycle in the fertility control model so that two foaling seasons occur between management actions. In the first mating period after fertility control application, fertility control effectiveness is $\pi_1 = 0.94$ and the intrinsic rate of growth is r_{t+1}. In the second mating period after management, fertility control effectiveness is $\pi_2 = 0.82$ and the internal rate of growth is r_{t+2}. A linear functional form is specified between the growth rate (r) and the proportion of females treated with contraceptive. Combined with the previously described parameters, a linear functional form yields equations [4] and [5].

$$r_{t+1}(X_t, Y_t) = r_0 - \pi_1 0.354\, Y_t/X_t \qquad [4]$$

$$r_{t+2}(X_{t+1}, Y_t) = r_0 - \pi_2 0.354\, Y_t/X_{t+1} \qquad [5]$$

The transition of the horse stock over time is then given by the theta logistic population growth function in equation [3] where the intrinsic rate of growth is $r_{t+1}(X_t, Y_t)$ in the second foaling period after fertility control management and $r_{t+2}(X_{t+1}, Y_t)$ in the third foaling period after

management. Furthermore, the specified growth function implies that variable $\tilde{X}_{t-1} = X_t/(1 + r_0)$.

Fertility control costs

The costs of fertility control management are parameterized as follows. The combined cost of obtaining contraceptives and administering them on the range is approximately $300 per horse (Bartholow, 2007). Fertility control management requires additional population monitoring compared to management with removals. The cost of fertility control monitoring (M) is approximately $7,000 per HMA per year (Bartholow, 2007). There are 18 distinct HMAs on BLM lands in Oregon and 84 in Nevada. Because management is considered at the state level, the models assume all HMAs on BLM lands must be monitored for the two years after fertility control is initiated. The second year of fertility monitoring is discounted so that if fertility control is initiated in fiscal year t, then monitoring costs for that management cycle equal $M_t = M + \rho M$. If fertility control is not initiated, then no monitoring costs are incurred during that management cycle.

Horse Population Net Benefits

Wild horse populations are associated with significant societal benefits. Large horse populations can impose also costs on stakeholders through displacement of alternative land uses and degradation to range lands. Pimentel et al. (2005) estimated that U.S. wild horse and burro populations cause $5 million in forage losses annually. Bastian, Van Tassell, Cotton, and Smith (1999) found that the marginal opportunity costs of additional horses on the range in excess of target population levels are well over $4060 in in 2015 dollars [23]. Wild horses also provide use and non-use benefits to wild horse supporters. However, these benefits are challenging to measure because their value is not revealed through market transactions[24].

The function describing horse population net benefits, $B(X)$, represents the aggregation of all costs and benefits attributable to that population. The shape of $B(X)$ depends on the shape of the marginal benefits and marginal costs functions. Bastian et al. (1999) found that the marginal costs of adding horses to a population were increasing through the population size associated with the $4060 figure mentioned above. Intuitively, adding horses to a small population under BLM management (i.e. management subject to an overall grazing limit) would displace less valuable wildlife and livestock resources compared to if the horse population was already large. Conversely, attempts in the economic literature to measure benefit functions for wildlife populations and habitats support decreasing marginal benefits (e.g. Rollins & Lyke, 1998; Layton, Brown, & Plummer, 1999), particularly when the wildlife population is above its minimum viable population (e.g. Ojea & Loureiro, 2009; Bandara & Tisdell, 2005). Decreasing marginal costs and increasing marginal benefits imply that the total net benefits function for horse populations, $B(X)$, is a single-peaked function. This analysis follows Rondeau and Conrad (2003) in assuming that total net benefits can be represented by a Gompertz function where:

$$B(X) = \begin{cases} 0 & \text{if } X = 0 \\ a\, X\, Ln\left(b/X\right) & \text{if } X > 0 \end{cases} \qquad [6]$$

The Gompertz is a single-peaked function that satisfies the characteristics of net horse benefits specified in section three (i.e. that $B_x > 0$ for $X \in [0, \bar{X})$ and $B_x < 0$ for $X \in (\bar{X}, \infty]$). The high-bound AML is assumed to be the population level $\bar{X}$ that corresponds with the maximum of $B(X)$. The marginal opportunity cost of an additional wild horse at high population levels is approximately $4,060 (Bastian et al., 1999), and the models assume that this is the marginal net benefit at carrying capacity. The resulting system of equations (i.e. $B_x(\bar{X}) = 0$ and $B_x(K) = -4,060$) is then solved for parameters a and b. In the Nevada model, parameters a and b are

equal to 2586 and 34824, respectively. The resulting function implies that a state population of 10 horses in Nevada produces $211 thousand in annual net benefits while a population at the high-range AML produces $33.1 million in annual net benefits. At carrying capacity, the Nevada hose population yields net benefits of negative $90.8 million annually. In the Oregon model, parameter a equals 2,586, and parameter b equals 7,380.

5.   Results

This section presents simulations of the specified optimal management models and compares them to current management practices. A 50-year time horizon is used to compare scenarios. Specifically, the 50-year net present value of scenarios is calculated under the status quo and under optimal population management. A long-term planning horizon is appropriate for this context because the public will manage wild horses for the foreseeable future.

Solving the Dynamic Optimization Problem

The solution to the problem in [1] is identified by solving the associated Bellman equation in [7] subject to the previously defined constraints and the terminal condition $V(T+1, X_t) = 0$, where T is the finite time horizon.

$$V(t, X_{t-1}) = \max_{\{Y_t\}} \left\{ \rho^t \left[B(X_{t-1}, Y_t) - C^g(Y_t) - C^a(ADPT_t) - C^{ur}(Y_t) - C^{ub}\left(Y_t \frac{F(X_{t-1})}{X_{t-1}}\right) - SC_t \right] \right\} + \rho^{t+1} V(t+1, X_t) \qquad [7]$$

The function $V(t, X)$ is the maximum achievable NPV benefits starting at time t with population level X and given action Y. All subsequent actions are assumed to be taken optimally, given the action taken in the current period. Bellman equations [8] and [9] are the equivalent for fertility-control and hybrid population management, respectively.

$$V(t,\ X_t) = \max_{\{Y_t\}}\{\rho^t B(\ X_t) + \rho B(\ X_t, Y_t) - C^g(Y_t) - C^{fc}(Y_t, HMA) - SC_t\} +$$

$$\rho^{t+1}V(t+1,\ X_{t+1}) \qquad [8]$$

$$V(t,\ X_t) = \max_{\{Y_t\}}\Big\{\rho^t B(\ X_t) + \rho B(\ X_t, Y_t) - C^g(Y_t + q) - C^{fc}(Y_t, HMA) - C^a(ADPT_t) -$$

$$C^{ur}(q) - C^{ub}\Big(q\frac{F(X_{t-1})}{X_{t-1}}\Big) - s\Big\} + \rho^{t+1}V(t+1,\ X_{t+1}) \qquad [9]$$

The Bellman equations were solved in MATLAB with a backward recursion algorithm that starts at the terminal period and works back to the initial period. The terminal period (T) is set to 100 years so that realization of the terminal condition is not taken into account in the optimal management simulations. Robustness checks with longer horizon models suggest that the solutions are stationary. To facilitate dynamic programming of the solution, the problems were discretized through rounding of the state variable to the nearest integer before each value calculation[25].

The Nevada and Oregon scenarios were simulated with a 50-year planning horizon for both the horse removal and fertility management models. The solutions to the Base optimal removal and optimal fertility control models, and their associated sensitivities, are summarized for Nevada and Oregon in Table 1 and Table 2, respectively. The population paths for the optimal solutions and the status quo scenario are presented for Nevada and Oregon in Figure 1 and Figure 2, respectively.

Status Quo Management Scenario

Status quo horse management practices were simulated under model assumptions to provide a baseline for comparison. BLM horse population estimates from 2009-2014 and associated management actions from 2009-2015 were evaluated to characterize current state-level management in Nevada and Oregon. Notably, the intensity of removal efforts varied substantially

from year-to-year in both states. In Nevada, annual gathers ranged from 1.5% to 30.5% of the estimated pre-foal population[26]. Annual Oregon gathers ranged from 0.0% to 54.0% of the pre-foal population. The status-quo management scenarios assume that future gather, removal, and fertility control efforts reflect a state's recent management practices. Specifically, the scenarios follow a six-year management cycle based on the proportion of horses managed in the six-year period from FY 2009-2014[27].

The periodic nature of the status quo scenarios gives rise to oscillations in the horse populations over time; as displayed in Figures 1 and 2. The populations increase in the earlier periods before leveling off in the later periods. The estimated NPV of status quo horse management over a 50-year time horizon is negative $1.97 billion in Nevada and negative $336 million in Oregon.

Base horse Removal Simulations

The Nevada and Oregon optimal removal scenarios involve an initial reduction of the population to a steady state equilibrium. In Oregon, the optimal program involves seven years of intensive removal effort at or near near Y^{max}. In equilibrium, 378 horses are removed from the range each year to maintain the steady-state population of 1,758 animals. The 50-year NPV of the Oregon optimal removals program is negative $28.3 million, a savings of $307.8 million compared to the status quo scenario. Similarly, the optimal removal program in Nevada involves intensive removals over the first 10 years of management. Following the initial population reduction, a steady-state management regime commences where 2,072 horses are removed annually to keep the population at 9,672 animas. The 50-year NPV of optimal removals in Nevada is negative $636.8 million, which represents a savings of $1.3 billion over that period compared to the status-quo scenario.

Evaluating the optimal management scenarios yields insights into the tradeoffs involved in maximizing population benefits over time. The absolute gather constraint is binding while the populations are reduced in the initial periods (i.e. $Y_t = Y^{max}$). At the optimal steady state, neither the Oregon nor the Nevada optimal gather program is bound by the gather constraints imposed on the model (i.e. $Y^{SS} < \min[Y^{max}, \delta X^{SS}]$). Together, these results imply that while the gather constraints regulate the speed with which the population is reduced to steady state, they do not constrain optimal steady-state management[28].

The NPV management costs incurred over a single fiscal year in steady-state are much higher for the larger Nevada population ($29.70 million) than they are for the smaller Oregon population ($4.26 million). Likewise, in steady-state, the larger Nevada population yields more annual net benefits ($32.03 million) than the Oregon population ($6.52 million). Together, these figures imply that the annual NPV optimal removals in steady-state is $2.33 million in Nevada and $2.26 million in Oregon. Thus, while the steady-state net population benefits ($B(X)$) from the Nevada population are nearly five times of those in Oregon, the populations yield similar steady-state program net benefits because of the higher costs of optimally managing the Nevada population.

Base Horse Fertility Control Simulations

The NRC report suggested that fertility control alone could not address the challenges associated with managing western wild horses[29], and the optimal fertility control scenarios support this sentiment. The optimal fertility control management program under model assumptions is to not undertake any management in both Oregon and Nevada. Without management, the horse populations grow to carrying capacity (K) and remain at that level for the duration of the management horizon[30]. Intuitively, it is impossible to reduce the population with fertility control

alone given the model gather constraints. Thus, it is optimal to just let the populations grow to their carrying capacity instead of trying to slow population growth through costly fertility control application. Because of this, the optimal fertility control scenarios represent a "no management" alternative and subsequent discussion of the management scenarios focuses on the removals and hybrid methods. The efficacy of fertility control management when it is applied in tandem with horse removals is explored in the hybrid management scenarios.

Base Hybrid Management Simulations

Fertility control alone is not a viable population management strategy. The hybrid scenarios explore the efficacy of fertility control management when applied in tandem with horse removals. The hybrid scenarios begin with intensive removals over successive years until the state population is brought within the AML range. Next, a program of fixed removals with optimally chosen fertility effort ensues. Fixed removals are undertaken at the lowest possible level subject to maintaining a stable population below carrying capacity, and the population never dropping below the low-range AML. When implemented in concert with removals, fertility control helps stabilize the horse population by decreasing the internal rate of growth. The Nevada hybrid scenario involves ten years of intensive removals that reduce the population to just over nine thousand horses. A steady-state gather program then begins on a two-year cycle that maintains a pre-gather population of 11,784. The steady-state program involves gathering 5,718 horses biannually, of which, 3,830 are removed and 944 are treated with fertility control. Adoptive homes are found for 150 of the removed horses and 3,680 go to long-term holding facilities. The hybrid program in Oregon involves seven years of removals followed by a biannual steady-state management program that maintains a pre-gather population of 2,136 horses. Every other year, 1,037 horses are

gathered, including 701 removals and 168 horses treated with fertility control. In Oregon, 392 of the removed horses are adopted and 309 are sent to long-term holding facilities.

The costs and benefits of the optimal removal and hybrid management programs over a two-year cycle are presented in Table 3. The steady-state NPV management costs of a single hybrid management cycle in Nevada are $55.7 million; a decrease of 4.4% compared to the NPV costs removals over the same time period. In Oregon, the NPV of steady-state hybrid management over a single cycle is $7.86 million, which represents a 6% reduction compared to removals. In terms of overall program net benefits, a two-year cycle of steady-state hybrid management yields NPV $8.11 million in Nevada and NPV $5.25 million in Oregon. Compared to optimal removals in steady state, hybrid management in steady state increases two-year net program benefits by 77.2% and 18.5% in Nevada and Oregon, respectively.

Model Sensitivities

With optimal solutions defined for the base scenarios, the analysis now turns to evaluating the sensitivity of the solutions to the specification of certain model parameters. The parameters evaluated with sensitivity analysis are the discount rate (δ), the cost of long-term holding, the internal rate of growth (r_0), the population where net benefits are maximized ($\bar{X}$) and the initial population (X_{-1}). The solution results for the sensitivity scenarios are summarized in Table 1.

Time preference parameter δ determines how the objective function weights future costs and benefits compared to current costs and benefits. In the base models, $\delta=4\%$. A sensitivity model where $\delta =10\%$ was solved and simulated to explore how assigning more value to current costs and benefits, and less value to future costs and benefits, influences the optimal management program. In the discount rate sensitivity scenarios, the optimal management program and the relative ranking

of programs according to net benefits remains the same as the base models across states and methods. The 50-year NPV program benefits, however, are higher in the discount rate sensitivity models. The reason for this is that the horse removals put BLM on the hook for the future costs of horse holding. With a higher discount rate, future holding costs are discounted more heavily, leading overall net benefits to increase relative to the base scenarios. While they yield higher overall NPV program benefits, the discount rate sensitivity scenarios are associated with a smaller increase in NPV program benefits compared to the status quo. The reason is that the status quo scenarios remove a relatively large number of horses in the later periods, and these removal costs are more heavily discounted in the sensitivity models.

Model sensitivity to the cost of long-term holding is evaluated next. Horses removed in recent years spend an increasing amount of time in short-term facilities because of difficulties securing long-term holding pastures for unadopted animals (BLM, 2014). Increasing the price paid for long-term holding is one means of securing additional long-term holding capacity. Thus, the long-term holding cost sensitivity scenario assumes that long term holding costs double from $1.52 to $3.04 per day to induce land owners to supply additional long-term holding capacity. Doubling long-term holding costs does not impact the optimal management program across methods. Further, the increase in program benefits relative to the status quo is larger in the high long-term holding cost scenario than in the base scenario. This result reflects the higher number of removals implemented in the status-quo vs. the optimal management scenarios. In the optimal removals and hybrid base scenarios, doubling the cost of long-term holding leads to doubling of the NPV net program losses under optimal management. This result underscores the importance of long-term holding costs in determining the present-value performance of management programs.

Sensitivity of model results to the specified internal rate of growth (r_0) is also considered. The National Research Council report (NRC, 2013). concluded that a mean annual population growth rate approaching 20% is a reasonable approximation for the free-ranging western horse population (NRC, 2013). The internal rate of population growth is specified to equal 28% based on a study of an Oregon wild horse herd. A sensitivity scenario is simulated where $r_0 = .2$ to evaluate how optimal management changes if the internal rate of growth were lower than in the base models [31]. With a lower growth rate, the sensitivity scenarios indicate that it is optimal to maintain smaller populations and decrease the number of horses removed in steady state. Conversely, fertility control effort is increased in the hybrid scenarios under a lower internal rate of population growth. Specifically, fertility control applications at the optimal steady-state increase by 43% and 46% in the Nevada and Oregon hybrid scenarios, respectively. The 50-year value of the management rises with a lower r_0, but the increase in program value relative to the status quo is smaller than in the base scenarios.

The next sensitivity examines an alternative parameterization of net population benefits function $B(X)$. In the base models the net population benefits function reaches a maximum at the high-range AML set by BLM. However, some members of the public are concerned that AMLs are too low to maintain genetically healthy herds (NRC, 2013). Thus, an alternative specification was developed that assumes $B(X)$ reaches its maximum at 150% of the high-range AML[32]. In Nevada, this sensitivity scenario implies that at its maximum, the value of $B(X)$ is about $67 million compared to $33 million in the base scenario. At carrying capacity, the Nevada sensitivity scenario implies that $B(X)$ equals negative $35 million versus negative $91 million in the base scenario. For optimal removals, the steady state population increases relative to the base scenarios. The increase is larger in the Oregon scenarios (15%) than in Nevada (0.4%). In both states,

removals increase proportionally with the steady-state population. In the hybrid scenarios, the optimal steady-state population and management program remains the same as in the base scenarios.

The final sensitivity scenario considers the possibility that horse populations are larger than the BLM estimates used to specify initial populations in the base models. The National Research Council Report concluded that BLM probably underestimates the number of wild horses it manages (NRC, 2013). Therefore, sensitivity scenarios were developed that assume the initial horse populations are 150% the size of those used in the base models. The NPV program value is sensitive to the specification of the initial population, particularly the Oregon scenarios. In Oregon, a 50% increase in the initial population results in seven times and ten times the NPV program losses compared to the base scenarios, using removals and hybrid methods, respectively. In Nevada, NPV program losses increase by 90% under optimal removals and 80% with hybrid management. The steady-state optimal management programs remain unchanged in the initial population sensitivity models.

Optimal Removals under Cost Minimization

Allowing horse populations to become self-limited can reduce population growth rates and potentially reduce the number of horses removed compared to current management. On the other hand, larger populations grow from a bigger base, and thus produce more horses annually for a given growth rate. If managers determine horse populations should not exceed some maximum level, the question arises as to whether it is cost effective to maintain self-limited populations just below the threshold, or if it is less costly to maintain a smaller, but faster growing population near the AML. To explore this, the next section examines optimal horse removals under a cost

minimization objective, where the net population benefits term $B(X)$ is dropped from the objective function. Dropping $B(X)$ from [1] and imposing a maximum population constraint frames management decisions in terms of cost effectiveness, where management costs are minimized subject to maintaining the hose population under some ceiling.

The minimum cost scenarios were run for Nevada optimal removals under Base model assumptions. If the maximum population constraint is set above 49,176, or roughly 80% of carrying capacity, then it is cost effective to manage a large population near the constraint. If the constraint is below this level then it is cost effective to manage a population of 9,672 horses, the optimal steady state solution to the base model in equation [1].

6.   Discussion

Dynamic, benefit maximizing models of wild horse management were developed for three non-lethal population control methods using published research on wild horse population biology and expenditure data from BLM. The optimal model solutions were compared to each other, and to a scenario that represents status quo management. The sensitivity of the solutions to certain specified parameters was evaluated. Finally, optimal removal models were developed with a cost-minimization objective to assess the cost effectiveness of maintaining populations under a specified level.

The model simulation results provide evidence of how to undertake state-level horse management to maximize benefits for stakeholders. Importantly, the results indicate that societally efficient management programs involve an initial reduction of state horse populations from their 2015 levels. This result is robust to a number of model specifications. For example, in the *Increase Population* sensitivity it is optimal to reduce the population to the Base model

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steady state if the initial populations are 50% greater than in the base models. In other words, the near-term costs of reducing the population are offset by the long term benefits of maintaining a smaller population at the optimal steady state. Of note, the 50-year NVP losses incurred in the *Increase Population* sensitivity scenarios are nearly double that of the base scenarios; underscoring the high costs of delaying implementation of an efficient population management program. The initial reduction characteristic of optimal management scenarios is also robust to the specification of net population benefits, $B(X)$. Specifically, it is still optimal to keep populations near the ALM if $B(X)$ is maximized at a level equal to 150% of the high-range AML. Here, the results suggest that the additional benefits of maintaining higher populations does not offset the additional management costs of maintaining larger populations that grow from a bigger base. The specified growth rate also does not appear to influence the initial reduction characteristic of optimal management. In fact, the *Decrease Growth Rate* scenarios are associated with lower optimal steady state populations (i.e. a larger initial reduction).

A second takeaway from the results is that fertility control alone is not an effective method for managing horse populations. The reason is that nearly all of the mares must be effectively treated to reduce horse populations with fertility control only. Further, the gather constraints imposed by the model make reducing or stabilizing horse populations with fertility impossible. If all mares in the population could somehow be effectively treated in each period, fertility control has the potential to slowly reduce the population at the mortality rate. However, it is unlikely all mares could be treated, and even if they could, fertility control would not produce a significant population reduction over the short term.

While fertility control alone is not an effective population management strategy, the hybrid management results indicate that fertility control can complement removal efforts. At the optimal

steady state, for example, there are 8% fewer horses removed over each two-year management cycle than there are with optimal removals in Nevada, and 7% fewer in Oregon. These avoided removals account for the higher NPV program benefits provided by the hybrid models compared to the optimal removal models. The effectiveness of fertility control in complementing removals is further evidenced by the increased in steady-state economic performance of the hybrid scenarios compared to the removals scenarios, as reflected in Table 3.

When framed in terms of cost minimization, the models yield the cost effective solution for keeping population under some specified maximum level. For removals in Nevada, it is cost effective to reduce populations and maintain them at the Base model steady state unless the population constraint is set above 49,176, or roughly 80% of carrying capacity. This result implies that managing medium sized populations is costly because many horses need to be removed to stabilize fast-growing populations that are not resource limited. Furthermore, maintaining small populations that are not resource limited is less costly than managing large, resource constrained populations unless the large populations are over 80 % of carrying capacity.

Separate models were developed for Nevada and Oregon, and comparison of the results across states yields additional management insights. Oregon contains 2.7 million HMA acres compared to 14 million in Nevada. Likewise, the Oregon models specify a smaller carrying capacity, AML, and smaller initial population to carrying capacity ratio compared to the Nevada models. Adoption demand higher in Oregon than in Nevada despite having a much smaller horse population. This allows Oregon to send a smaller proportion of removed horses to long-term holding. These state-specific management differences hint at the difficulties inherent in managing the large Nevada population. Though the larger Nevada population yields nearly five times population benefits at the optimal steady-state, Oregon and Nevada yield comparable 50-

year program values due to the high costs of managing the Nevada population. Moreover, the Base management scenario with the lowest NPV program value is Status-quo for Nevada and Fertility Control (i.e. no management) for Oregon. This result also reflects the high costs of reducing and maintaining the large Nevada population.

Overall, the simulation results indicate that significant economic gains can be realized with a more strategic approach to wild horse population management. Relative to the Status Quo scenario, the results indicate that implementing hybrid management will result in 50-year NPV program value savings of $1.3 billion in Nevada and $308 million in Oregon. Realizing these savings, however, is a matter of incurring short-term costs to realize future benefits. The Status Quo scenario is the most intensive management method across the 50-year management horizon. In the Nevada status quo scenario, nearly 260 thousand horses are taken to long-term holding facilities over the management horizon, compared to around 150 thousand with optimal removals and 130 thousand with hybrid management. While they involve fewer overall removals, the optimal scenarios implement more intensive removals in the initial periods. Thus, the optimal scenarios are associated with lower NPV program benefits in the early periods and make it up in the later periods. This dynamic is depicted in Figures 3 and 4. The NPV management program costs over time are presented in Figures 5 and 6. In the initial periods cumulative NPV program benefits are larger and cumulative management costs are lower for the status quo management scenarios compared to the optimal scenarios. Nevada NPV cumulative program benefits from the optimal removal and hybrid scenarios surpass those from the Status Quo scenario starting in period 10. In Oregon, this occurs starting in year 9 for the removals scenario and in year 10 for the hybrid management scenario. Cumulative NPV management costs are higher in the optimal scenarios than in status quo management until the 28[33] period in most scenarios[33]. The

simulations predict significant gains from implementing optimal population management. However, realizing these gains requires enduring the short-term pain of intensive initial management in return for higher population benefits and lower management costs in the future.

Appendix

Appendix A1: Hybrid Population Control

$$\max_{\{Y_t\}} \sum_{t=z+1,z+3,z+5,\dots}^{\infty} \rho^t \left[B(X_t) + \rho B(X_{t+1}) - C^g(Y_t + q) - C^{fc}(Y_t, HMA) - C^a(ADPT_t) - \right.$$

$$\left. C^{ur}(q) - C^{ub}\left(q\frac{F(X_{t-1})}{X_{t-1}}\right) - s \right] \quad (A.1)$$

Subject to:

$$X_{t+2} - X_t = F_{t+1}(X_t, Y_t) + F_{t+2}(X_{t+1}, Y_t) - q\left[1 + \frac{q}{F_{t+2}(X_{t+1}, Y_t)}\right]$$

$$Y_t \leq \begin{cases} Y_{max} \\ \delta\tilde{X}_t \end{cases}$$

X_{-1} is given

$$\tilde{X}_t^{min} \geq AML \; \forall \; t$$

$$ADPT_t = \begin{cases} q[1 + \frac{F(X_{t-1})}{X_{t-1}}] & if \; q[1 + \frac{F(X_{t-1})}{X_{t-1}}] \leq \gamma_t \\ \gamma_t & if \; q\left[1 + \frac{F(X_{t-1})}{X_{t-1}}\right] > \gamma_t \end{cases}$$

$$M_t = \begin{cases} 0 & if \; Y_t \leq \gamma \\ M + \rho M & if \; Y_t > \gamma \end{cases}$$

Where:

$$\tilde{X}_t = \frac{X_{t-1}}{(1 + r_0)} + q$$

$$\tilde{X}_t^{min} = \frac{X_{t-1}}{(1 + r_0)}$$

$$X_0 = F(X_{-1}) + X_{-1} - q\left[1 + \frac{q}{F(X_{-1})}\right]$$

$z = initial \; reduction \; periods$

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Tables and Figures

Table 1   Optimal Management Characteristics for Nevada Scenarios

	Scenario	Optimal Steady-State Management Program					50-year Net Program Benefits (millions of USD)		
		Pre-gather population	Removals	Fertility treatments	Total gathers	Percent gathered	Cumulative benefits	Change from Status Quo	Change from Base
	Base	**9,672**	**2072**	**0**	**2072**	**21%**	**-$636.8**	**$1,331.6**	
	Increase discount rate	9,672	2,072	0	2,072	21%	-$367.6	$391.5	$269.1
Removals	*Increase holding costs*	9,672	2,072	0	2,072	21%	-$1,274.5	$1,405.1	-$637.8
	Decrease growth rate	9,112	1,488	0	1,488	16%	-$196.6	$837.7	$440.2
	Increase benefits	9,712	2,080	0	2,080	21%	$54.1	$848.6	$690.8
	Increase population	9,672	2,072	0	2,072	21%	-$1,153.8	$1,040.4	-$517.1
	Base	**61,592**	**0**	**0**	**0**	**0%**	**-$1,786.5**	**$181.8**	
	Increase discount rate	61,592	0	0	0	0%	-$765.7	-$6.7	$1,020.8
Fertility control	*Increase holding costs*	61,592	0	0	0	0%	-$1,786.5	$893.1	$0.0
	Decrease growth rate	61,592	0	0	0	0%	-$1,674.4	-$640.2	$112.1
	Increase benefits	61,592	0	0	0	0%	-$557.4	$237.2	$1,229.1
	Increase population	61,592	0	0	0	0%	-$1,945.0	$249.2	-$158.5
	Base	**11,784**	**3,830**	**944**	**5,718**	**49%**	**-$593.6**	**$1,374.7**	
	Increase discount rate	11,784	3,830	944	5,718	49%	-$358.4	$165.5	$235.2
Hybrid	*Increase holding costs*	11,784	3,830	944	5,718	49%	-$1,200.9	$2,086.0	-$607.3
	Decrease growth rate	10,232	2,199	1,352	4,903	48%	-$115.5	$440.7	$478.1
	Increase benefits	11,784	3,830	944	5,718	49%	$120.4	$201.0	$714.0
	Increase population	11,784	3,830	944	5,718	49%	-$1,121.3	$1,600.6	-$527.7

Table 2   Optimal Management Characteristics for Oregon Scenarios

	Scenario	Optimal Steady-State Management Program					50-year Net Program Benefits (millions of USD)		
		Pre-gather population	Removals	Fertility treatments	Total gathers	Percent gathered	Cumulative benefits	Change from Status Quo	Change from Base
Removals	**Base**	**1,758**	**378**	**0**	**378**	**22%**	**-$28.3**	**$307.8**	
	Increase discount rate	1,758	378	0	378	22%	-$20.6	$92.2	$7.7
	Increase holding costs	1,758	378	0	378	22%	-$107.1	$319.4	-$78.8
	Decrease growth rate	1,647	270	0	270	16%	$33.5	$183.4	$61.8
	Increase benefits	2,020	432	0	432	21%	$95.7	$185.7	$124.0
	Increase population	1,758	378	0	378	22%	-$195.5	$206.6	-$167.2
Fertility Control	**Base**	**13,053**	**0**	**0**	**0**	**0%**	**-$364.0**	**-$27.8**	
	Increase discount rate	13,053	0	0	0	0%	-$149.4	-$36.5	$214.6
	Increase holding costs	13,053	0	0	0	0%	-$364.0	$62.5	$0.0
	Decrease growth rate	13,053	0	0	0	0%	-$328.1	-$178.2	$35.9
	Increase benefits	13,053	0	0	0	0%	-$104.7	-$14.7	$259.3
	Increase population	13,053	0	0	0	0%	-$397.4	$4.7	-$33.4
Hybrid	**Base**	**2,136**	**701**	**168**	**1,037**	**49%**	**-$18.9**	**$317.2**	
	Increase discount rate	2,136	701	168	1,037	49%	-$17.8	$95.0	$1.1
	Increase holding costs	2,136	701	168	1,037	49%	-$90.8	$335.7	-$71.9
	Decrease growth rate	1,857	402	245	891	48%	$41.9	$191.8	$60.8
	Increase benefits	2,136	701	168	1,037	49%	$108.3	$198.4	$127.3
	Increase population	2,136	701	168	1,037	49%	-$190.3	$211.8	-$171.4

Table 3 Value of a Two-year Optimal Management Cycle at the Steady State (millions of USD)

State	Scenario	Net Population Benefits	Management Costs*	Net Program Benefits*
Nevada	Removals	$62.8	$58.3	$4.6
	Hybrid	$63.8	$55.7	$8.1
	difference	*+1.6%*	*-4.4%*	*+77.2%*
Oregon	Removals	$12.8	$8.4	$4.4
	Hybrid	$13.1	$7.9	$5.2
	difference	*+2.5%*	*-6.0%*	*+18.5%*

* Values include the NPV lifetime management costs of caring for removed horses. For discounting purposes, t=0 in the first year of the optimal management cycle and t=1 and in the second year.

Figure 1 Population Paths for Nevada Base Simulations
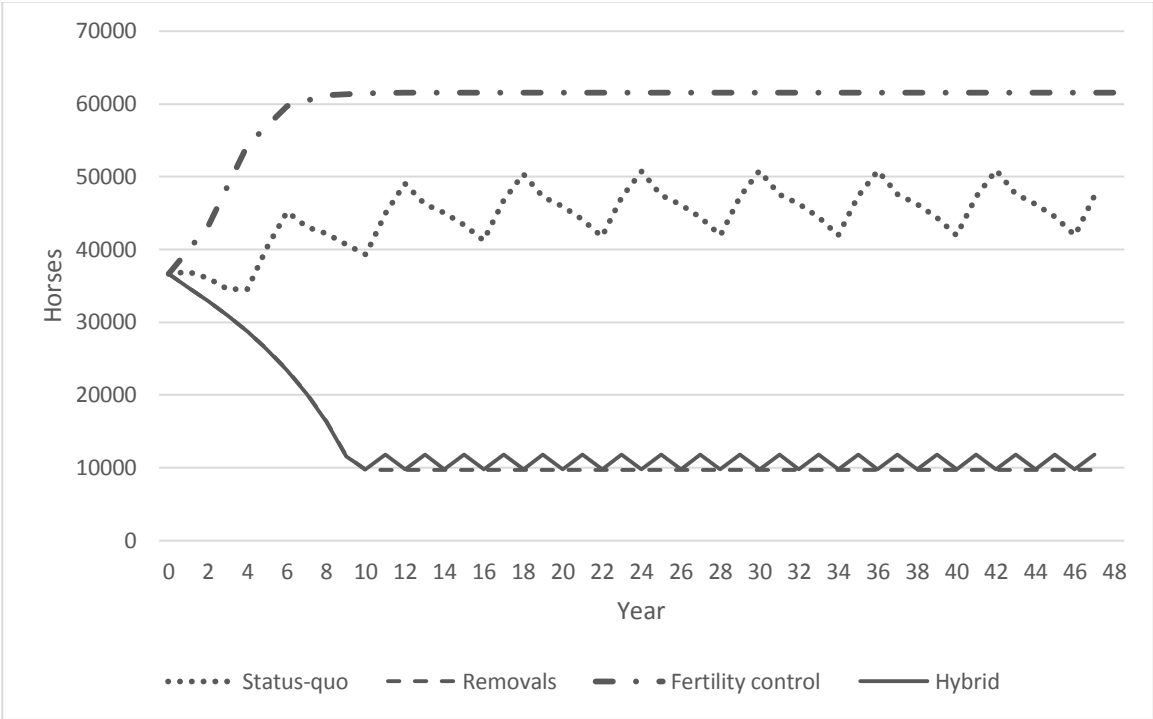
Figure 2 Population Paths for Oregon Base Simulations
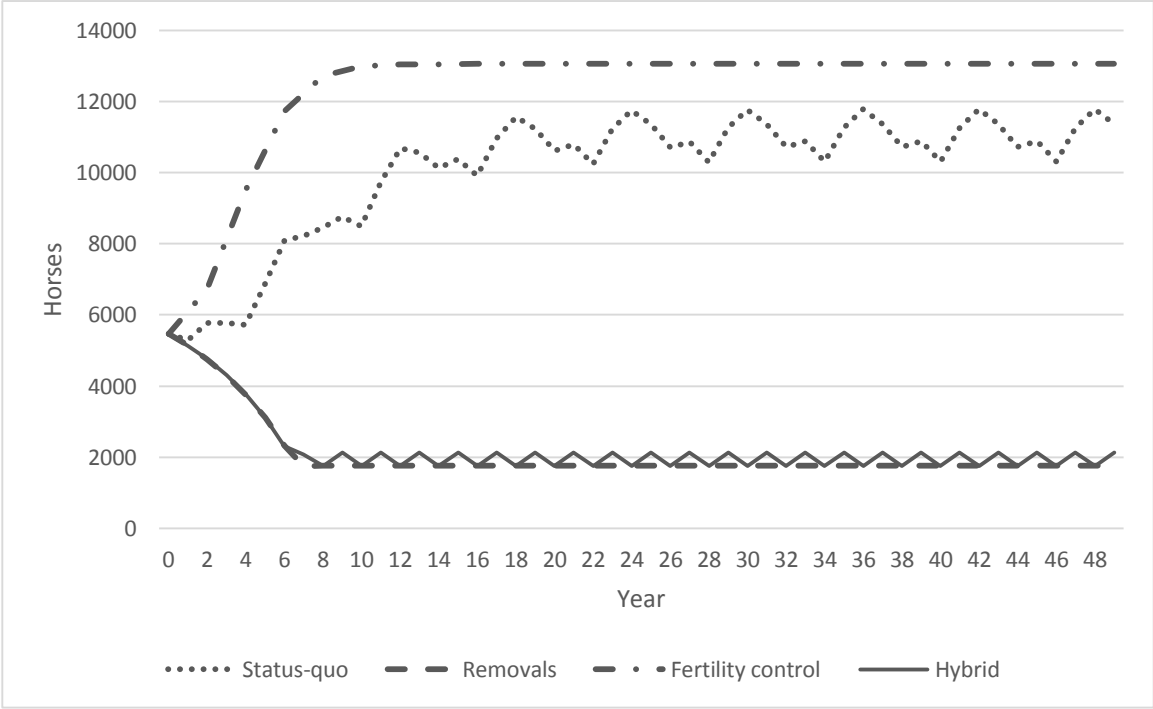
Figure 3 Cumulative NPV Net Benefits of Management Programs for Nevada Base Simulations
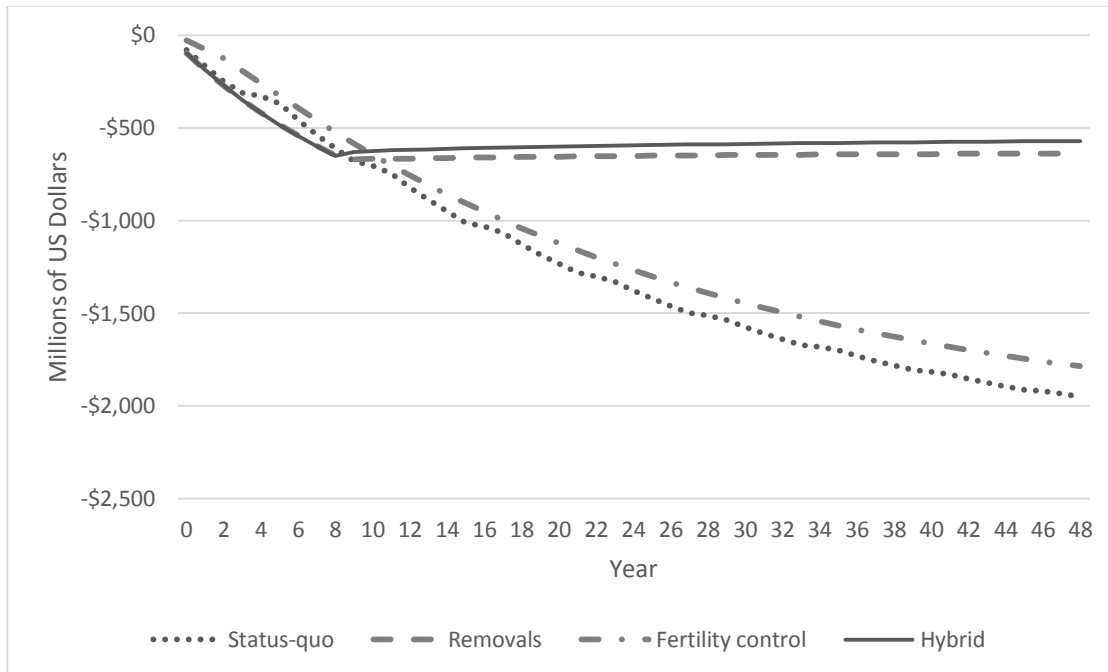

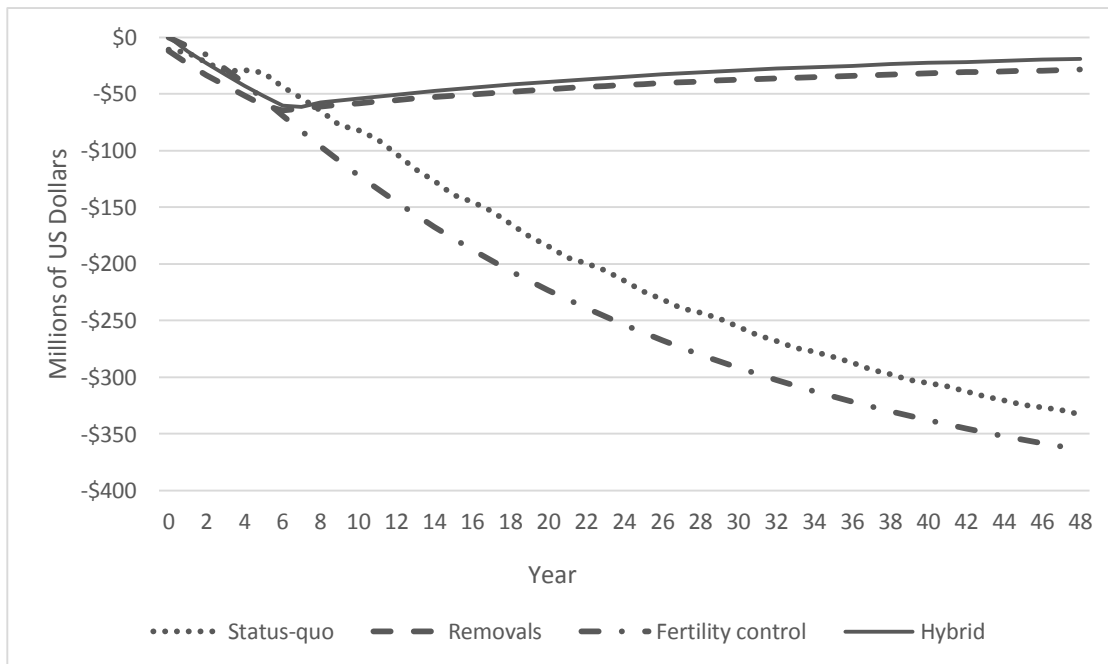Figure 4 Cumulative NPV Net Benefits of Management Programs for Oregon Base Simulations

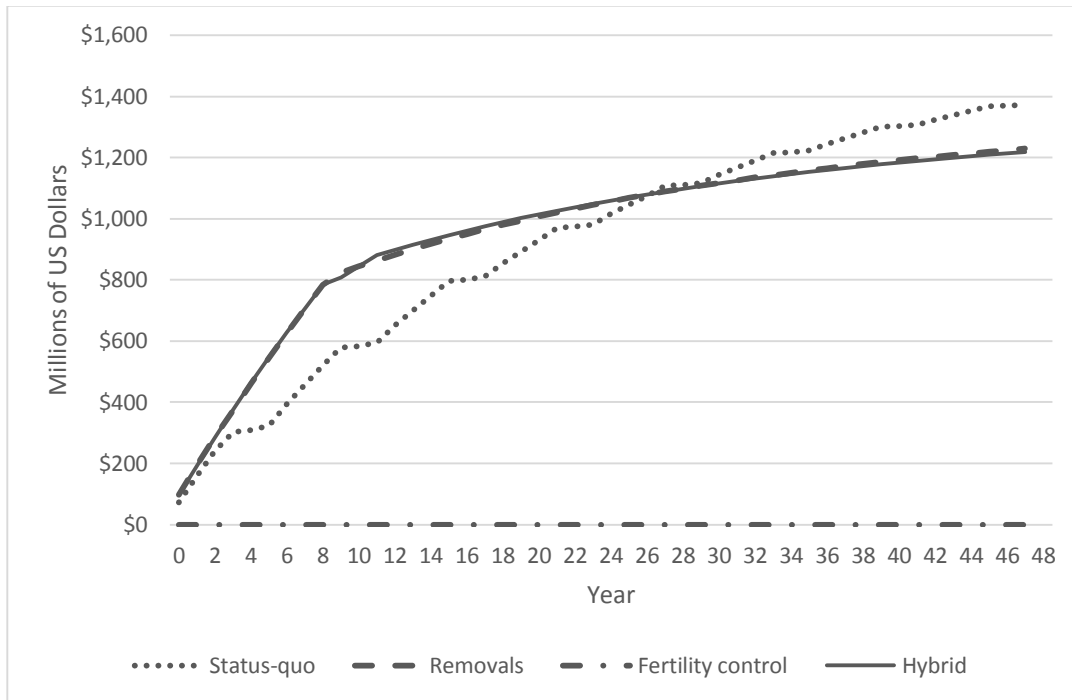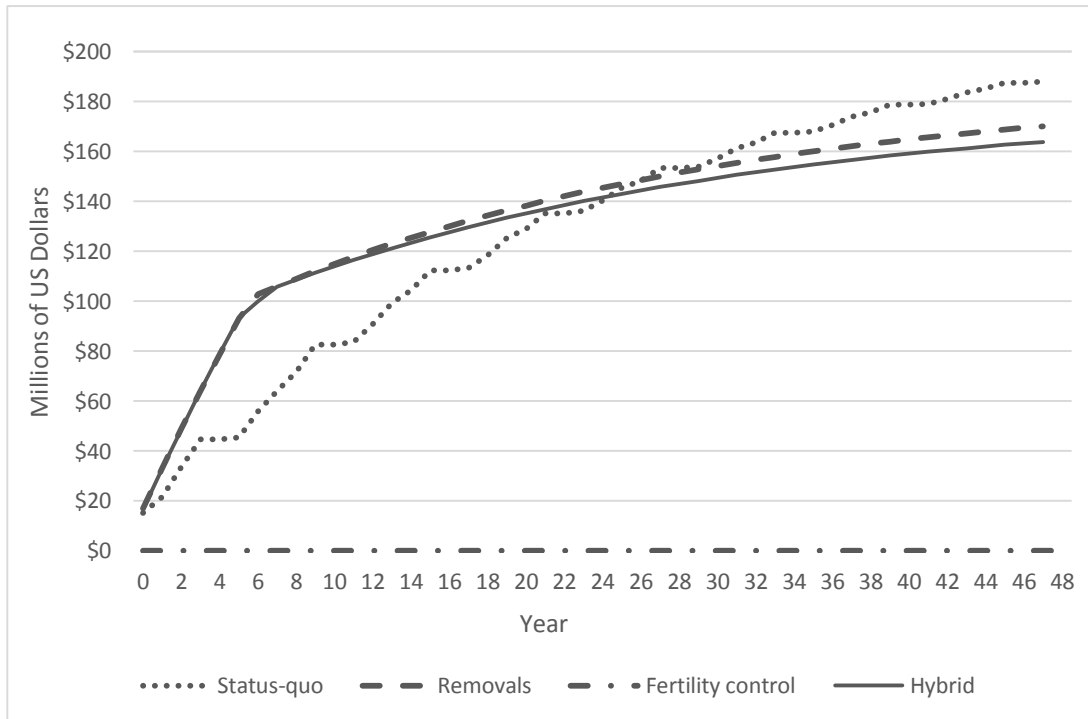Figure 5 Cumulative NPV of Wild-Horse Management Costs for Nevada Base Simulations

Figure 6 Cumulative NPV of Wild-Horse Management Costs for Oregon Base Simulations

Notes

1 Bear, wolf, coyote, cougar, beaver, geese, alligator, porcupine, and deer populations are actively managed in North America.

2 This refers to the minimum feasible level of management, not the minimum population

3 This practice was banned by law between 1988 and 2004 and currently is not advocated by BLM policy

4 NRC 2013 pg. 7

[5] The optimal time to administer PZP-22 for maximum duration is fall or winter

[6] This assumption also facilitates computational tractability in solving the optimization problem

[7] Fertility control management requires additional population monitoring (Bartholow 2007)

[8] The lower bound is the previous period population assuming no fertility control effort and no density-dependent population effects. Thus, by definition: $\tilde{X}_{t-1} \leq X_{t-1}$.

[9] In terms of population reduction per unit of gather effort.

[10] Removals continue until further reduction results in the population dipping below the low-range AML given the specified level of fixed removals.

[11] Due to data limitations, this analysis focuses on wild horse populations and does incorporate burro-specific cost or population biology parameters. In 2015, BLM estimated there were 2,611 burros in Nevada (8.6% of total) and 49 burros in Oregon (1.1% of total)

[12] $\rho = 1/(1 + \delta)$, where δ is the discount rate

13 All values represent 2015 USD

[14] The candidate covariates included the number of gathers completed, the state population size, and the average population size of managed HMAs.

[15] The length of stay in short-term holding for removed horses has increased significantly in recent years due to difficulty with securing additional long-term holding capacity.

[16] From the BLM instructional guidance representative of 2003 procedures

[17] The authors analyzed demographic data from horses in holding from 2007-2011

[18] For each fiscal year 2010-2015, the number of horses in holding (short and long) is calculated as the average of monthly holding inventories reported by BLM. The per day holding cost is then calculated as the average number of horses in holding divided by the total (short and long) holding expenditures reported by BLM for that fiscal year.

[19] Roughly the distance from existing short-term holding facilities outside of Reno, NV and Burns, OR to existing long-term holding facilities in Kansas and Oklahoma

[20] BLM estimates total miscellaneous costs equal $851 for unadopted horses and $210 for adopted hoses (4/14 BLM advisory board meeting). Miscellaneous costs for unadopted horses are discounted to present values under the assumption that total miscellaneous costs are split equally between short-term holding and long-term holding.

[21] The NRC report noted that fertility control has: "… the potential to reduce population growth rates and hence the number of animals added to the national population each year" (NRC, 2013, p 13)

[22] Effectiveness is defined as the percentage of treated females that to not give birth.

[23] Bastian et al. (1999) estimated the opportunity cost of an additional horse on the range in Wyoming under the assumption that BLM adjusts other livestock and wildlife populations to maintain a target level of grazing.

[24] BLM is planning a socio-economic benefits study to investigate public preferences for wild horses and their management.

[25] Discretization also involved grouping the horses into units to limit the dimensionality of the linear programming problem. The Nevada models use 8-horse units and the Oregon models use 3-horse units.

[26] The status-quo gather proportions were constructed with the March 1 BLM population estimate in the denominator and the horses gathered over the subsequent 12 months in the numerator.

[27] Subject to state gathers not exceeding Y^{max} or δX_{t-1}

[28] This was confirmed by solving the model without gather constraints. The unconstrained model reduces the population to steady state in a single period.

[29] "…the effects of fertility intervention, although potentially substantial, may not completely alleviate the challenges BLM faces in the future in effectively managing the nation's free-ranging equid populations, given legislative and budgetary constraints." NRC 2013, Pg. 13

"Thus, the potential implementation of broad-scale fertility-control management to aid in curbing population growth rates will be confronted by the challenge of treating the large number of horses that will probably be required to have appreciable effects on horse population demography." NRC 2013, Pg. 67

[30] Nevada population reaches K by end of fourteenth year of management. Oregon population reaches carrying capacity by end of year sixteen.

[31] Note that this sensitivity also involved adjusting [4] and [5], the formulas for how fertility control impacts population growth

[32] Under the "Increase benefits" sensitivity scenario: a=3485.62 and b=52237.22 in Nevada; a=3485.62 and b=11071.56 in Oregon.

[33] The exception is the Hybrid scenario in Oregon, where the crossover occurs in period year 26.