Controlling Horse Populations in the Western United States

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1 Introduction

Since colonization across the Atlantic, humans have introduced a variety of herbivores into North America. "Wild" horses, *Equus ferus caballus* are derived from domesticated stock and persist in feral populations, many of which are found across the Western United States [1]. Their populations are approaching $100,000$ individuals and can double about every 4 years [1][2], causing undue pressure on the environment. Wild horses are regarded as everything from invasive pests to charismatic symbols of the West, complicating management options. The current political climate pits diverse stakeholders against each other: ranchers concerned for their cattle, animal rights groups concerned about humane horse treatment, and the government concerned about managing rangeland health and cutting costs. Scientists will continue to be called upon to best inform management options. Considering the intensive resources needed for large-scale experiments in Western rangelands, there is ample opportunity for theoretical modeling of horse population management strategies.

Current management efforts have not been effective and may now imperil the environment. Within the United States, management of horse populations primarily falls to the Bureau of Land Management (BLM) [3]. Since the ratification of the Wild Free-roaming Horses and Burros Act of 1971, this agency has been tasked with maintaining the health and numbers of these now-protected wild horses [4]. However, their strategy has been predominantly limited to gathering excess horses into off-range corrals and pastures in the hopes that they would be adopted [2]. Adoption rates have been far lower than gathering rates, causing an excess of approximately $40,000$ horses off the range in combination with the approximately $60,000$ non-captive horses [1][2]. Continued growth of the non-captive horse population can pressure fragile ecosystems. For example, their grazing can increase land erosion [5], disturb native fauna and trophic interactions [6][7], and facilitate the spread of weeds and invasive species [5][8]. Economic concerns exist as well. Particularly, ranchers fear that their cattle face excess competition [9][10]. A prompt response is critical to prevent further horse overpopulation and its adverse effects.

The BLM already employs a model for population growth, but it may be outdated for current management needs. This model, called WinEquus, considers age and sex for survival and fecundity probabilities, density dependence, and environmental stochasticity [11][2]. These parameters can be applied under four simulated management conditions: lack of management, removals, control of female fertility, and both removals and control of female fertility. Evidently, there remain gaps in the current model, and the BLM's use of the WinEquus remains dubious, lacking transparency [2]. A recent BLM report [1] presents management scenarios and economic estimates that are not fully compatible with WinEquus. To achieve their appropriate management level (AML) of $26,715$, the BLM proposes four options:

I. Full release of limitations (allowing for currently outlawed population control such as euthanasia and slaughter for meat).

II. Temporary PZP immunocontraception with minimal sterilization.

III. Some sterilization alongside removals and an adoption incentive.

IV. Intense sterilization paired with an adoption incentive[1].

Option I employs the use of all legal authorities from the Consolidated Appropriations Act (2017) by allowing sale without limitation, euthanasia and limited use of contraceptive techniques including PZP and sterilization. Option II focuses on the use of PZP and minimal use of sterilization techniques, while Option IV incentivizes adoption and employs aggressive sterilization of 18,000 wild horses each year. Option III relies on the sterilization of 3000 horses in conjunction with the capturing of horses, while maintaining current levels of PZP usage. In addition, this option introduces the use of incentivization of adoption to move additional horses out of off-range facilities.

Our model aims to directly apply these proposed management options to best inform the BLM's strategy. We simulate all four of their options, including in our model variables for euthanasia/slaughter, PZP immunocontraception, sterilization, removals, and adoption. Additionally, our model aims to inform management decisions by quantifying the economic ramifications of the proposed interventions.

2 Methods

2.1 Linear Difference Equation Model

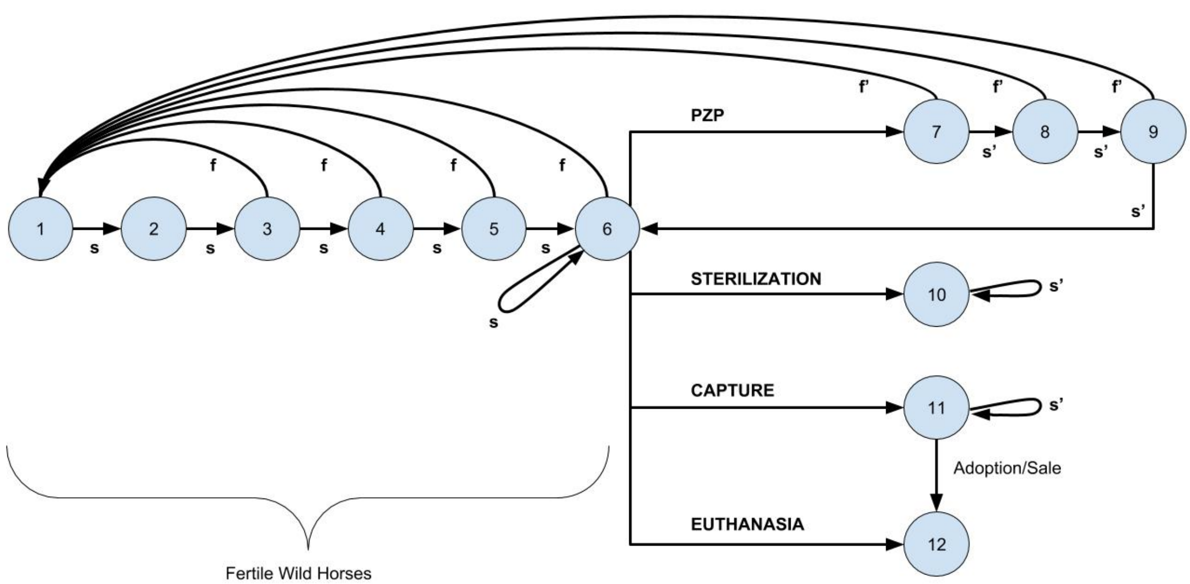


Figure 1: Visual representation of the Markov chain used in this model. Classes 1-6 represent horses in the wild with natural fecundities and survival. Classes 7-12 model explicitly different BLM interventions. Specifically, nodes 7-9 represent horses in various stages of the 3-year effects of PZP on fecundity and survival. Node 10 represents sterilized wild horses. Node 11 contains horses that are captured by BLM. Finally, class 12 includes all horses removed from BLM care, either by euthanasia or by adoption or sale. Particular fecundity and survival values vary between age classes, but are represented with the same variable for simplicity in the figure above.

Drawing from empirical research conducted in the past half-century in the United States, we develop a mathematical model to forecast the population level of horses in the West. Specifically, we use a set of linear difference equations to describe the changing population levels in various age classes, characterized by fecundity level and survival rate. We develop a linear transformation matrix to find the horse population at time $t + 1$ given the population at time t. Essentially, we use a Leslie matrix to describe the population of feral horses. However, instead of only using age classes to characterize sections of the population, we explicitly model different managerial and contraceptive interventions. The distribution of the horse population can be thought of as a Markov process, since a mare's probability of occupying a given class at time $t + 1$ is dependent only on her state at time t. Explicitly modeling females, we are able to extrapolate implicit conclusions about males and the general horse population in the future.

The population dynamics, and potential managerial interventions, can be visualized using Figure 1. The corresponding Matrix describing the process above can be found in Figure 2.

$$L = \begin{bmatrix}
0 & 0 & f_{2-3} & f_{3-4} & f_{4-5} & f_{5+} & f_{p,1} & f_{p,2} & f_{p,3} & 0 & 0 & 0 \\
s_{0-1} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & s_{1-2} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & s_{2-3} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & s_4 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & s_5 & s_{5+}(1-c-x_w-p_w)-\alpha_w & 0 & 0 & s_{p,3} & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & (s_{5+})p_w & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & s_{p,1} & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & s_{p,2} & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & (s_{5+})x_w & 0 & 0 & 0 & s_x & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & (s_{5+})c & 0 & 0 & 0 & 0 & s_x(1-\alpha_c) & 0 \\
0 & 0 & 0 & 0 & 0 & \alpha_w & 0 & 0 & 0 & 0 & (s_x)\alpha_c & 0
\end{bmatrix}$$

Figure 2: Leslie matrix L describing horse population dynamics.

The parameters determined by the population are:

- f_{i-j} is the fecundity for a female between ages i and j.
- s_{i-j} is the survival rate for a female between the ages of i and j.
- $f_{p,n}$ for $n \in 1, 2, 3$ are the reduced fecundities over 3 years of a female who has been treated with PZP. The PZP has time-variant effects, so we model these explicitly over a 3-year time period.
- $s_{p,n}$ for $n \in 1, 2, 3$ are the increased survival rates over 3 years of a female who has been treated with PZP. The PZP has time-variant effects, so we model these explicitly over a 3-year time period.
- s_x is the increased survival rate of a female that does not give birth (either fully sterilized or held in captivity).

The parameters that the BLM has control over are:

- c, the proportion of females the BLM captures each year.
- p_w, the proportion of wild females that the BLM will administer PZP to each year.
- x, the number of females that the BLM will sterilize each year. x_w is the proportion of wild horses, x_c is the proportion of captured horses (that are then released into the wild). $x_c + x_w = x$
- α is the number of horses that get adopted, bought, or euthanized. The twelfth node in our chain is essentially there to represent horse that are fully removed from the BLM's care. α_w is the number of wild horses that the BLM will euthanize each year. α_c is the number of captive horses that the BLM adopt out or sell. While the BLM does not have complete control over α_c, which depends on factors like demand, we model it as a managerial decision because the various policy alternatives include allowing horse sales for a wider variety of purposes, which would effectively increase α_c. $\alpha_c + \alpha_w = \alpha$.

2.2 Modeling Assumptions

In this model, the horse population changes in discrete time. Each time-step represents one year. Feral horses reproduce during a yearly foaling season, so a discrete-time approach avoids the periodic oscillations in fertility and reproduction that occur in continuous time. Also, most relevant literature reports survival probability and fecundity as annualized values [12][13]. Another important aspect of our model is that it is deterministic, rather than stochastic. Of course, we do not claim to encode every causal factor that impacts the wild horse population.

The numbers that we report can be thought of as an expected future horse population.

Moreover, mares are modeled explicitly and stallions are modeled implicitly. Conclusions about the total wild horse population use the assumption of an equal gender distribution, such that total wild population $n_{tot} = n_{mare} * 2$. While this result may not be true for captive populations, where females are expected to have increased survivorship, we believe that the assumption is reasonable for wild horses, where survivorship for females is not inflated [14]. Harems are also not explicitly modeled, because the impact on females of the different social behaviors of harem leaders and subordinate males can be thought of as an average over all members of the population.

It is important to note that interventions in this model are made only on horses that are at or above 5 years of age. This gives horses a total of four years with non-zero fecundity before the BLM is able to intervene. We believe this assumption to be reasonable because BLM policies will not be able to perfectly target mares right as they become fertile. Furthermore, we assume that wild, non-contracepted horses above the age of 5 maintain a constant fecundity and survival rate for the rest of their life. This assumption allows us to model all adult wild horses in one class (represented by node 6 in Figure 1). In reality, the fecundities and survival rates do seem to level off for mares above 5, as observed in Garrott in 1990 [13]. Thus, we do not explicitly model ages above 5, and we conveniently model all our managerial interventions by altering the edges on node 6. However, we do model explicity the effects of various management decisions on survival rates. Professor Dan Rubenstein finds that mares have a higher survival rate when they have fewer foals [14]. We account for this change by altering the current survival term s_i associated with a contracepted horse in class i, as follows:

$$s_i = \frac{s_{5+} + 1 - f_i}{2} \tag{1}$$

Another important simplification that we make in this model is a lack of density dependence. Feral horses currently are thought to be growing at a geometric rate [15][16], but of course we do not expect geometric growth to persist indefinitely. Therefore, our model offers predictions that are accurate in the short-term. Discussion of longer-term impacts will cover the feasibility and economic considerations of various interventions, but numerical output by our difference equation model will be imprecise after many years.

With regards to the administration of PZP, in our model, PZP affects horses for 3 years, and horses inevitably spend one year with natural fecundity before being re-administered. We believe this to be reasonable because administration is hard to keep track of. The particular modeling assumption that horses must spend at least one year between each PZP treatment with natural fecundity may mean that effects of PZP are under-represented by our model. In particular, we include this note because PZP has been known to lead to infertility after multiple treatments [14]. We do not model this effect, and require re-administration to continue fecundity suppression indefinitely.

Finally, the BLM is unconcerned with horse populations that have been adopted or sold. Therefore, our class 12 encompasses adopted, sold, and euthanized individuals. Accordingly, the survival rate is zero for class 12.

2.3 Obtaining Empirical Data

The empirical data used to substantiate our model were obtained from research by academics and the Bureau of Land Management. The baseline survival rates and fecundities of horses in various classes were acquired from a 1990 study of a feral horse herd in Montana [13]. The BLM releases publicly available annual data on adoption, gather and removal rates, population-growth suppression treatments, budgetary concerns and up-to-date horse population estimates [3]. The effects of PZP interventions are drawn from Bartholow, et al. (2007) [17] and can be seen in Table 1. The initial population vector used in this model is based on data from the Pryor Mountain Wild Horse Range in Montana [18].

Year 1	Year 2	Year 3	Year 4
94%	82%	34%	0%

Table 1: Effectiveness of PZP over 4-year period.

In considering the success of the implementation of various interventions, it is important to make note of their economic feasibility. As can be seen in Table 2, there are certain costs associated with all the components of horse population control techniques, split into three major categories. The first two categories reflect data taken directly from the Bureau of Land Management's 2018 report to Congress [1] and a published study of the effectiveness of PZP [19]. The third category, opportunity costs, is less straightforward - it represents the BLM's loss of income as a result of devoting less land to ranchers to be used for cattle grazing. The BLM leases its land by Animal Unit Months, or AUMs, which allow ranchers to graze one steer for one month. According to the Food and Agriculture Organization of the United Nations, cattle graze for four months out of the year [20], and in this model it is assumed that one horse displaces one steer from grazing on the range. Thus, each horse on the range denies the BLM income from four AUMs annually, as represented by the value shown in Table 2.

Category	Action	Cost
Horse Placement	Holding	$1823.25 per head annually
	Removal	$1000 per head
	Adoption	$1931 per head
Fertility Control	PZP	$230 per dose
	Ovariectomy	$300 per treatment
	Euthanasia	$1000 per head
Opportunity Costs	Opportunity Costs	$7.48 per head annually

Table 2: Economic Impacts of Various Horse Population Control Techniques

3 Results

3.1 Population Control Analysis

In our model of horse populations, a controlled population is one which is either constant or shrinking year to year. We infer this control from our modified Leslie matrix L by the dominant eigenvalue λ_{dom} where the population is stable if $\lambda_{dom} \leq 1$ (see Table 2 & Equation 3).

$$n_{t+1} = L \cdot n_t \tag{2}$$

$$n_{t \gg t_0} = \lambda_{dom} \cdot n_{t-1} \tag{3}$$

where $n_{t \gg t_0}$ would approach the dominant eigenvector associated with eigenvalue λ_{dom}.

We can determine the level of control different intervention practices can exert on the horse population by examining how the λ_{dom} of L changes as the intervention values (percentage of horses captured, sterilized, etc.) change. We find that PZP contraception alone cannot control the wild horse population, while sterilization and capture can, albeit with over a 60% intervention rate (see Figure 3).

3.2 Projections Using Current BLM Strategy

Currently, the BLM is capturing horses at a rate of 3.14% of the wild population per year, with a low rate of PZP contraception (0.6% per year) and no permanent sterilization of animals left on the range [3]. Under these intervention conditions, our model shows positive geometric growth in the horse population, with costs initially receding as the capture rate is below the rate of removal from captivity (see Figure 4). Therefore, we explore alternative rates of intervention suggested by the BLM.

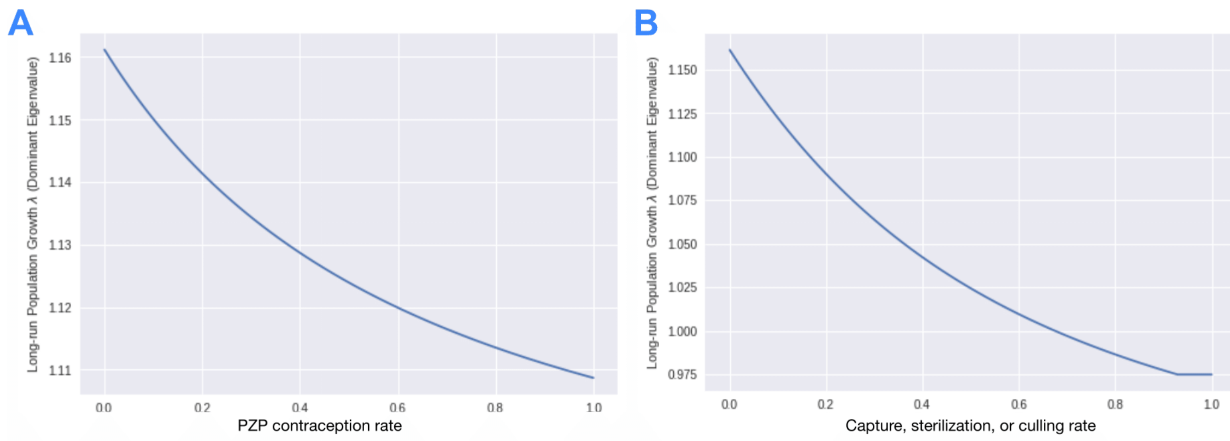


Figure 3: Dominant eigenvalue analysis of Leslie matrix L (see Table 2) compared to the rates of three intervention techniques amongst 5+ year old wild mares: **A** PZP contraception; **B** capture and removal from range or permanent sterilization. It is important to note that the effects of capturing and of sterilizing are the same on long-term growth rates because they both limit the number of offspring by the same amount. Note also that PZP contraception can not bring $\lambda_{dom} \leq 1$, while capture and sterilization have the exact same long term effect on the population as the effected individuals no longer contribute to reproduction in either case.

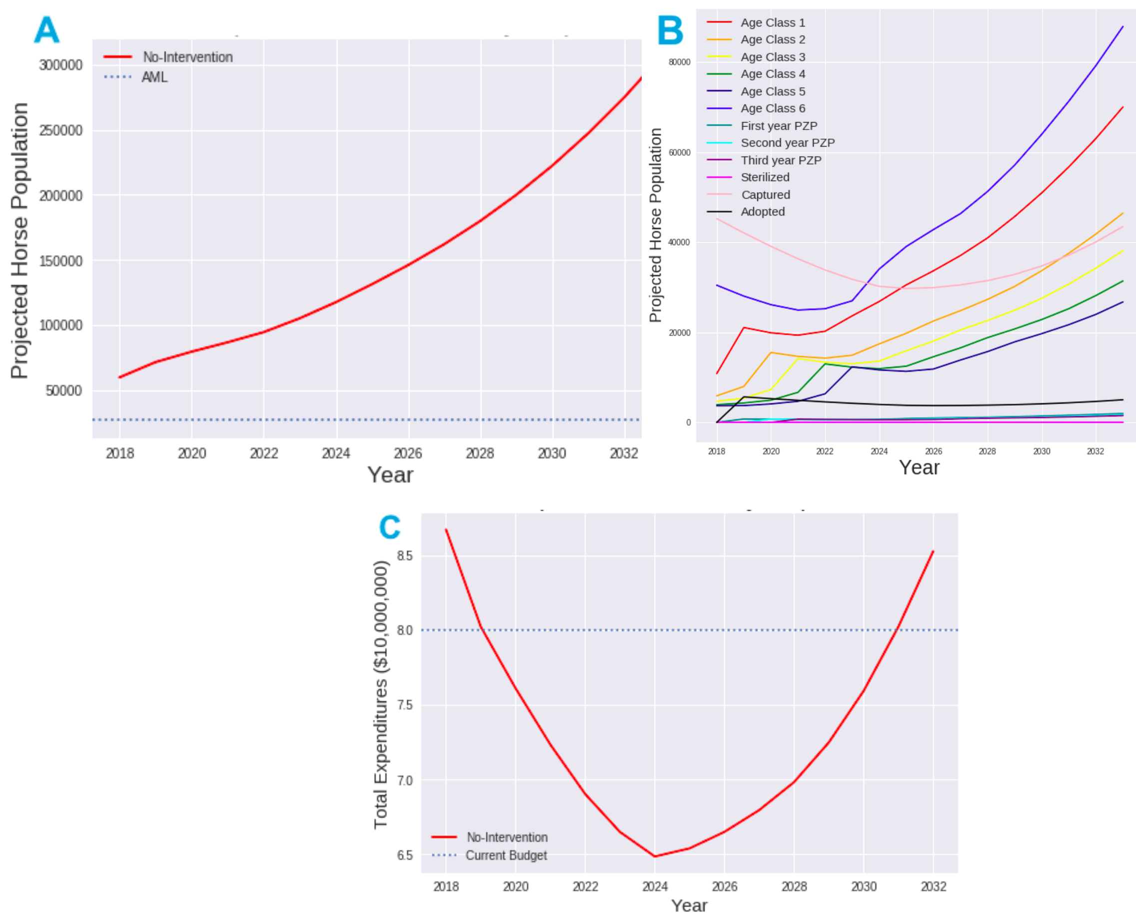


Figure 4: 15-year projections of total (**A**) and class-specific (**B**) wild horse populations, with corresponding program expenditures (**C**) Modeled with current BLM intervention conditions $c = 3.14\%$, $x_w = 0\%$, $p_w = 0.6\%$, and $\alpha_c = 2.44\%$. Note that the captured population class initially decreases until the capture rate c equals the removal rate α_c.

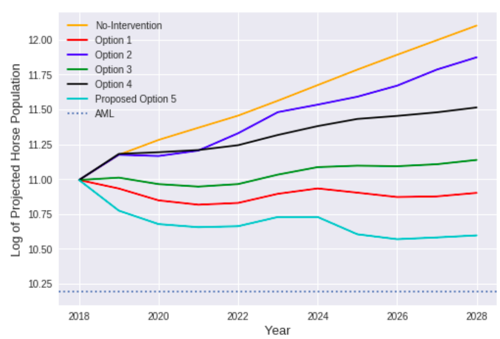
3.3 Exploring the BLM's Proposed Options

We modeled Options I - IV using the parameters shown in Table 3:

	p_w	x_w	c	α_w	α_c
Option I	0.6%	5%	55%	10%	100%
Option II	70%	5%	3.14%	0%	2.44%
Option III	0.6%	2.5%	5%	0%	6.22%
Option IV	0%	15%	3.14%	0%	6.22%

Table 3: Parameters used in modeling the four options proposed by the BLM.

In their Report to Congress, the BLM asserts that the four management options proposed would achieve national AML before 2030. The options detailed in the report provide a framework for improving the management of wild horses, but do not provide quantitative descriptions of the actions required to attain such a goal. The results we attain from our model of these recommended strategies suggest that the BLM was too liberal in their estimations of the impact of each of their management options. Figure 5 shows that none of the management options reach AML by 2028.



(a)

Management Strategy	Long-Term Growth Rate (Dominant Eigenvalue)
Current Strategy	1.11
Option I	0.998
Option II	1.086
Option III	1.011
Option IV	0.994
Option V	0.975

(b)

Figure 5: Total wild horse population growth over a 10-year period (a) and long-term growth rates (b) with current strategy and 5 proposed strategies.

According to Figure 5(a), Option I (free limitations) is the most effective of the BLM's proposed strategies in reducing population growth in a 10-year time span. In the first two years of its implementation, we estimate that Option I would effectively reduce the population size by more than 30%. In following years, however, the results point to a less marked decrease in population size, as the population size reaches a flatline. The long-term growth rate, given by the dominant eigenvalue of the Leslie matrix, is below 1, indicating declining populations over time.

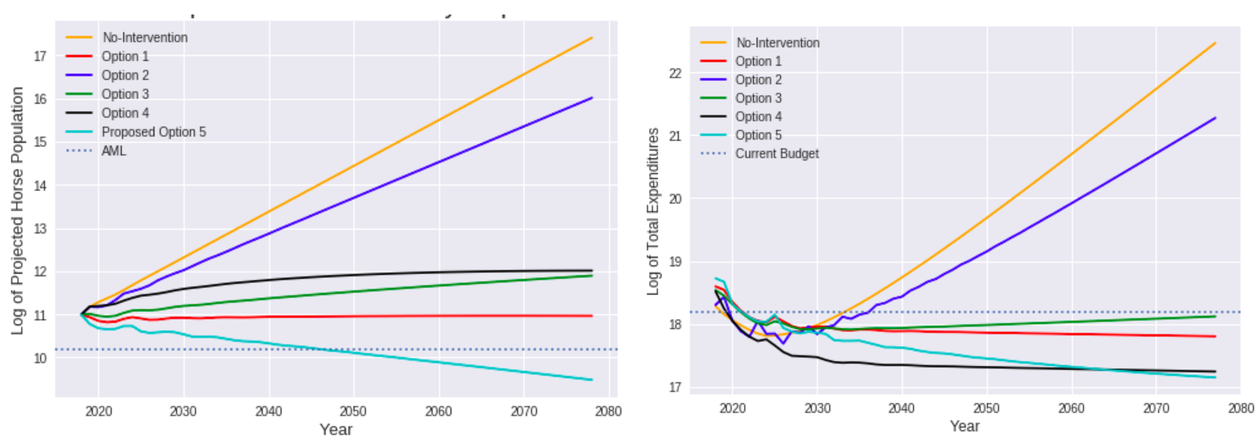
After Option I, our model predicts Option III (sterilization and capture) to be the next most successful in reducing the population size of wild horses in the first 10 years. However, by looking at the dominant eigenvalue, we see that with Option III the population size continues to increase, albeit slowly. Accordingly, our model predicts Option I to be the only strategy to lead to an overall decrease in wild horse population by the benchmark year of 2030.

In the first year of implementation, Option II (extensive use of PZP) and Option IV (sterilization and adoption) do not seem to curb population growth. By the fifth year of implementation, the impact of Option II and Option IV on the horse population becomes distinct. According to estimates from our model, the use of PZP does not prevent exponential growth in the horse population, while the effect of adoption and sterilization in decreasing the rate of growth becomes unambiguous. This is supported by the long-term growth rates for Options II and IV reported in Figure 5(b), in that the former has a dominant eigenvalue that is greater than 1, and the latter does not.

Because these four options do not appear to be drastic enough to make a difference in the future, we propose here a fifth, more extreme scenario: sterilizing the same percentage of horses as in Option III, capturing the current percentage of horses, and euthanizing all the rest (meaning as many other adult horses as possible). All of the captive horses would be adopted or sold without limitations. This would be politically very difficult to achieve, but it is a valuable comparison to the other options in that it shows just how dramatic the BLM's course of action needs to be in order to see changes in the next few decades. As shown in Figure 5(b), this scenario yields the lowest long-term growth rate.

3.4 Economic Considerations

Figure 4 shows the projected increases in wild horse populations and Wild Horse and Burro Program expenditures over a 25-year period under current intervention levels and makes it clear that it ecologically or economically feasible to continue with the current strategies. The dotted line in the graph of total horse population represents the appropriate management level, while the dotted line in the graph of total expenditures represents the Wild Horse and Burro Program's current budget of $80 million. By the year 2031 the BLM's expenditures would begin to extend well beyond its current budget.



(a) (b)

Figure 6: Total wild horse populations (a) and program expenditures (b) over a 60-year period with current strategy and 5 proposed strategies, plotted on log scale

While it can be seen in Figure 5(a) that none of the four options proposed by the Bureau of Land Management will be able to reduce the wild horse populations to AML in the 10-15 year timeframe they suggest, Figure 6(a) extrapolates the population dynamics for a longer time period and shows that the extreme proposed Option 5 is capable of achieving AML in 27 years. Figure 6(b) shows the economic implications of these five strategies in relation to the BLM's current budget for the Wild Horse and Burro Program. Despite the initial spike above the current budget, this graph shows that in the long term Options I (allowing for euthanasia and slaughter), III (introducing sterilization), IV (aggressively sterilizing) and the proposed Option V are all economically feasible in the long term, and in fact would require a lower budget than is currently needed because there would be fewer horses off-range in the BLM's care.

3.5 Applications of the Model

This model can be used by the Bureau of Land Management to determine which of the 5 strategies examined in this study to use in a given year. In particular, we've developed a tool for the BLM to sequentially alter its strategy based on the current population level and distribution of wild and captive horses. This dynamic strategy determines whether the population size needs to increase or decrease (i.e., if it is above or below AML), and finds the most cost-effective intervention option to make the necessary changes. Interventions $i \in (0, ..., 5)$ are compared by calculating one-year population effects per dollar spent:

$$\zeta_i = \frac{(change\ in\ wild\ population)_i}{(cost)_i} \tag{4}$$

This quantity represents the population reduction per dollar spent by BLM, for each intervention. When current population $n < AML$, the dynamic strategy picks an intervention option that maximizes ζ_i. When current population $n > AML$, the dynamic strategy picks an intervention option that minimizes ζ_i.

Figure 7(a) shows the results of a 100-year projection of BLM management using the dynamic strategy. As might be expected, the program suggests using option 5 to reach AML, and then switching between no-intervention and option 5 to maintain a population near AML. 7(b) and (c) show the resulting population sizes and annual costs, respectively, and demonstrate the effectiveness of this model in maintaining AML while staying below budget.

The dynamic strategy tool can be generally used to compare and combine any number of intervention options that can be represented by a Leslie Matrix in our model. The only constraint, of course, is computation time. Thus, even if Option 5 proves unfeasible for BLM, the dynamic strategy tool can still help make optimal management decisions.

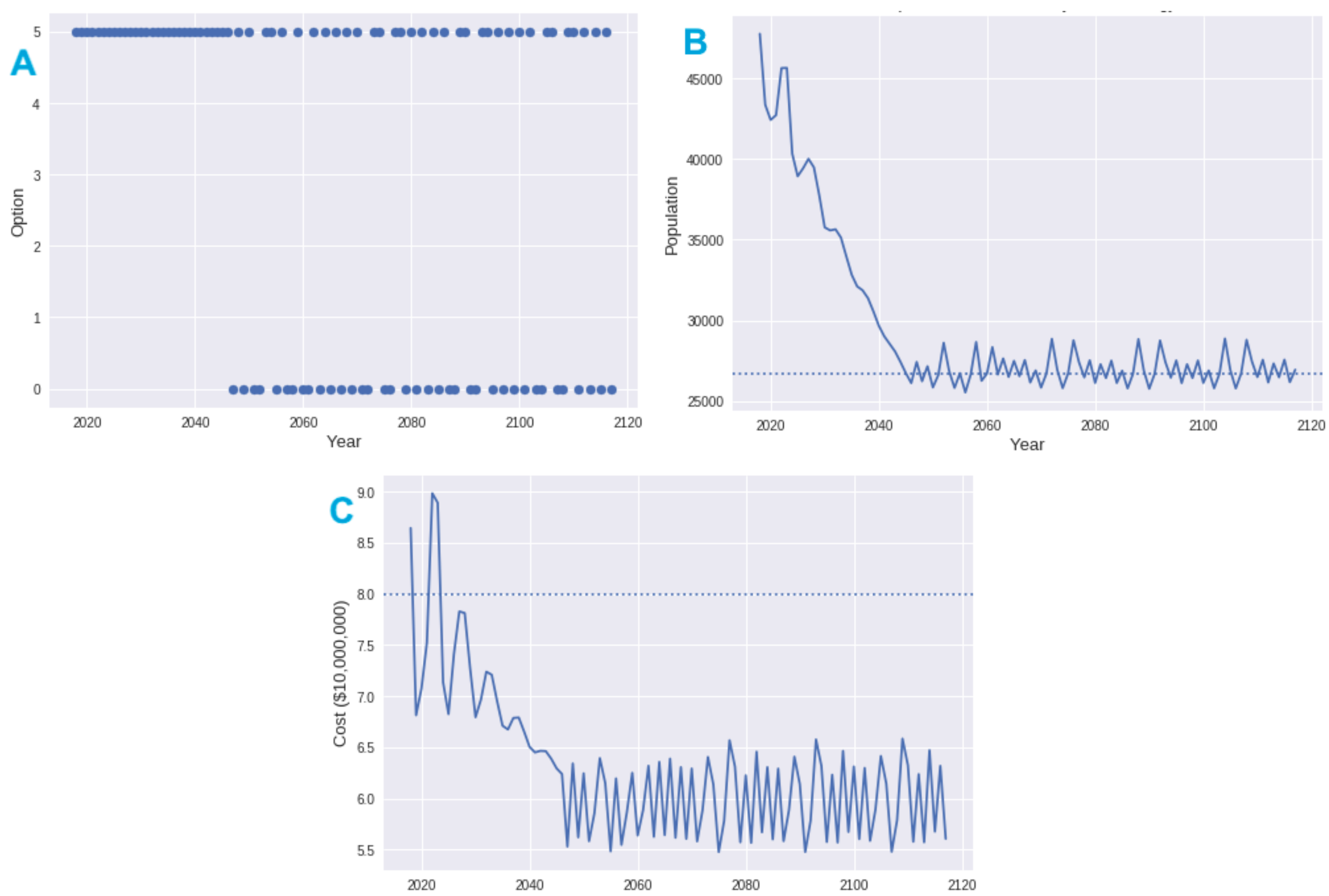


Figure 7: Optimal strategy at each time step (a) and resulting population dynamics (b) using the dynamic strategy approach. The economic ramifications (c) are included to show that this particular strategy is economically feasible over a 100-year period.

4 Conclusion

Reviewing similar scenarios in other systems highlights the necessity of checking the growth of this wild horse population before they cause serious ecosystem harm (either in the form of biodiversity reduction or more derivative effects, like erosion.) Unchecked growth has been observed to exacerbate natural erosion patterns [21], along with a variety of indirect ecological effects that come with the increase in a population of grazers such as horses.

For example, their presence can impact the establish-ability of invasive species [8], or can even affect predation rates of other native species through their rampant destruction of the habitat [6]. Already in the United States, the increase in behaviorally-dominant wild horses has been shown to displace other native species – such as the American pronghorn mule deer [22]. Clearly, there is potential for ecological crisis on a fairly large scale if the population of feral horses is allowed to blossom without management. As we focus on this issue, we must consider the realistic possible avenues for treatment and amelioration of this predicament.

Treatment is restricted in some ways by societal and cultural beliefs, which dictate a certain measure of respect and sympathy for these horses. The BLM has struggled with effective management strategies that do not offend sympathetic conservationists. The American Wild Horse Campaign (AWHC) and the Cloud Foundation are just two examples of groups that consistently have protested and fundraised against the very same management methods we are presenting. They lobby under a variety of moral grounds: inhumane treatment of animals, artificially lowered natural population levels, and an "unfair" distribution of land use to favor privately owned livestock, to name a few [23].

Bearing that in mind, it is necessary that we consider the ethical ramifications of our possible treatment methods. It is undeniable that the cheapest possible method for lowering the population of feral horses would be euthanasia, or cheaper still, controlled hunting. It would be simple, highly effective, and incredibly efficient, even more so than the BLM's Option I of no restrictions. It is, however, unpalatable to several entities, not the least of which being the groups mentioned above. Frankly, the argument can be applied to any population which is growing relatively unchecked. It would be highly effective, efficient, and benefit the net welfare of the planet to begin culling the human population, but as of yet that is still a fear for a dystopian future rather than a government policy. Similarly to the plight of the American wild horse, it is simply not ethically viable to conduct "genocidal" euthanasia. We do not mean to compare the value of a human life to that of a horse, but the point is clear. On occasion, the modeled economic or environmental benefit is not worth the ethical cost of the actions required by said model. To that end, we have generated a range of models, reflecting the degrees of ethical plasticity advertised in treatment options. It is our belief, established and evidenced in this report, that the most effective and sufficiently ethical management strategy is Option IV.

Option IV, better described as a combination of aggressive sterilization and an emphasis on adoption, will sufficiently control the population and be a cheaper economic policy within 60 years. It will accomplish this with an added benefit - it is the most palatable option for horse conservationists. This will greatly facilitate any effective rollout, as the main hurdle to a policy change is the issue of ethically handling this rampant population growth.

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