Brian Folt
U.S. Geological Survey
Fort Collins Science Center
Fort Collins, CO 80526, USA
Email: bfolt@usgs.gov
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Multi-objective Modeling as a Decision-support Tool for Feral Horse Management

Brian Folt[1] *, Kathryn A. Schoenecker[1,2], and L. Stefan Ekernas[3]

[1]U.S. Geological Survey, Fort Collins Science Center, 2150 Centre Ave, Building C, Fort Collins, CO 80526, USA

[2]Ecosystem Science and Sustainability, Colorado State University, Fort Collins, CO 80523, USA

[3]Denver Zoological Foundation, 2300 Steele Street, Denver, CO 80205, USA

* Corresponding author e-mail: bfolt@usgs.gov

Abstract: Decisions related to controversial problems in natural resource management receive the greatest support when they account for multiple objectives of stakeholders in a structured and transparent fashion. In the United States, management of feral horses (*Equus caballus*; horse) is a controversial multiple-objective problem because disparate stakeholder groups have varying objectives and opinions about how to manage fast-growing horse populations in ways that sustain both natural ecosystems and healthy horses. Despite much decision-support research on management alternatives that prevent excessive population size or cost, horse management decisions still receive resistance from a variety of stakeholder groups, potentially because decisions fail to explicitly or transparently account for multiple objectives of diverse stakeholders. Here, we used a predictive model for horse populations to evaluate the degree to which alternative management strategies involving removals and fertility control treatment with the immunocontraceptive vaccine PZP-22 maximize four objectives in horse management: maximize ecosystem health, maximize horse health, minimize effects on horse behavior, and minimize management cost. We simulated scenarios varying in management action, frequency, magnitude, and starting population size over a 10-year interval and evaluated scenario performance with a weighted multiple-objective utility reward function. Management involving high-magnitude removals along with PZP-22 treatment generally outperformed other alternatives by achieving higher reward relative to alternatives in two scenario analyses. Simulation of 1372 scenarios at five starting population sizes generally found that management with biannual removals and two doses of PZP-22 treatment for half of eligible females during years 1 and 5 generated the most rewarding outcomes. However, a removal scenario with more frequent PZP-22 application generated the greatest reward when starting population size was already within target population size range. Our paper demonstrates how values and objectives of diverse stakeholders can be used to support management decisions in ways that might lead to greater acceptance of decisions by a broad array of stakeholder groups.

Keywords: decision analysis, *Equus caballus*, feral horses, population growth, PZP-22, stakeholder input, structured decision making, wildlife management.

Predictive modeling is a useful tool for understanding complex ecological systems, predicting how ecosystems or species respond to disturbance or management, and providing clarity to problems and conflict in natural resource management (Norton 1995, Addison et al. 2013). For managers making decisions about natural resource management, predictive models provide a data-driven approach to predict outcomes of alternative management actions, identify preferred alternatives that maximize management objectives, and support management decisions in a structured, transparent, and outcome-based manner (Runge et al. 2020). Predictive modeling can be particularly useful for contentious problems in natural resource management, where diverse stakeholders have multiple, competing objectives, and it can be challenging to reach consensus about a management decision(s) that satisfies many or all stakeholders. However, difficult decisions receive the greatest support when they collaboratively engage stakeholders and account for multiple stakeholder objectives in a structured and transparent fashion (Williams et al. 2007, Voinov and Bosquet 2010, Gregory et al. 2012, Converse et al. 2020). In this paper, we describe how accounting for multiple objectives during predictive modeling of management alternatives for free-ranging feral horse (*Equus caballus*; horse) populations can be used to support management decisions in ways that involve diverse stakeholders and may garner broader support than previous decision-support models that focused on one or few objectives.

In many parts of the world, management of feral horse and burro (*E. africanus* and *E. asinus*) populations can reasonably be considered a multiple-objective problem (Danvir 2018, *sensu* Converse 2020). In the United States, horse and burro populations that occur on designated federally-owned lands are protected by federal law ("The Wild and Free-Roaming Horses and Burros Act"; Public Law 92-195 1971) as "living symbols of the historic and pioneer spirit of the West (Norris 2018)." The Department of Interior Bureau of Land Management (BLM) and Department of Agriculture U.S. Forest Service (USFS) are tasked with managing feral equid populations for a “thriving natural ecological balance” on designated federal lands where they occur (Public Law 92-195). However, with high survival rates and few predators, feral equid populations are characterized by relatively high population growth rates (Ransom et al. 2016, Garrott 2018); herds can quickly grow to exceed target population sizes established by management agencies, disrupting the ecology and conservation of sympatric wildlife in western rangeland ecosystems and other public land multiple-use benefits (Beever and Aldridge 2011, Danvir 2018, Hall et al. 2018, Davies and Boyd 2019, Eldridge et al. 2020, Coates et al. 2021).

To comply with Public Law 95-514 (1978), federal agencies conduct gathers (i.e., ‘round-ups’) to capture animals, remove excessive individuals to achieve target population sizes (i.e., Appropriate Management Levels [AML]), and treat a proportion of females with some type of fertility control agent (e.g., vaccines that reduce reproductive rates, such as PZP-22; Rutberg et al. 2017) before being released back to the range. Together, management seeks to prevent horses from disrupting the “thriving natural ecological balance” of ecosystems specified by the Wild and Free-Roaming Horses and Burros Act (Public Law 92-195) by maintaining populations within target population size ranges (i.e., an ecosystem health objective), while also maintaining high-quality health of horses by preventing negative density-dependent effects on horse health at high population density (i.e., a horse health objective). Contemporary management actions have not been able to maintain populations within target population size ranges, as populations in many areas of the American West exceed established management targets (Garrott and Oli 2013, Garrott 2018).

On the other hand, certain stakeholder groups (Carlisle and Adams in press), such as wild horse advocates, often express different values and objectives to be maximized during management. Horse advocacy groups can be vocal proponents for a 'hands-off approach' and allowing horses and their environment to self-manage, a perspective that can view horse management unfavorably because gathers involve capturing animals, removing individuals from the wild, and disrupting social groups (Carlisle and Adams in press). Given these concerns, an objective of horse advocacy groups is to minimize handling (gathers, removals, fertility control treatment; Carlisle and Adams in press) to avoid disrupting the behavior and social groups of horse populations (i.e., a horse behavior objective). However, the horse behavior objective likely trades-off in performance with the ecosystem health and horse health objectives, because minimizing management would fail to control population growth and result in excessively large population sizes that risk disrupting ecosystem health (Davies and Boyd 2019), other uses of public land (Danvir 2018) and horse health due to severe resource limitation (Scasta et al. in press).

Scasta (2019) argued that due to the deep, emotionally laden co-evolutionary history between horses and humans, more consideration of human emotions toward horses could benefit the development of effective management decisions for horse populations. To this end, we suggest that multi-objective decision analysis provides an opportunity to incorporate the values of diverse stakeholders in the horse management decision problem (National Research Council 2013), which can be framed as objectives that can be modeled explicitly and potentially maximized during management decisions. Indeed, given the high level of public interest and scrutiny in horse and burro management decisions (Symanski 1996, Wagman and McCurdy 2011, Scasta et al. 2018), wildlife managers and decision makers will best garner stakeholder support when management decisions are derived from transparent, robust, science-based management plans that explicitly account for objectives of multiple stakeholders (Voinov and Busquet 2010, Gregory et al. 2012).

While decision-support models to date have been useful for understanding the population dynamics and management to achieve target population size ranges of feral horse populations in the western United States, most analyses have focused on evaluating the performance of management alternatives for maximizing two objectives: decreasing population size and future population growth rates so that herds are managed within target population size ranges (i.e., AML; National Research Council 2013) in ways that might maximize the health of both ecosystems and horses, and decrease overall cost of management (Garrott and Taylor 1990, Garrott 1991, Garrott et al. 1991, 1992, Garrott and Siniff 1992, Coughenour 2002, Gross 2000, Ballou et al. 2008, Bartholow 2007, de Seve and Boyles Griffin 2013). However, despite analytical and conceptual advances of models and their utility for supporting decisions, horse management decisions still receive resistance from various stakeholder groups, potentially because decisions fall short of accounting for objectives of diverse stakeholders in an explicit and transparent manner (National Research Council 2013).

Population models evaluating horse management alternatives at the scale of individual populations have generally supported a management strategy where managers first reduce abundance to within target population size ranges through gather and removal, then treat a proportion of the remaining female population with a fertility control agent (e.g., immunocontraceptive vaccine) to decrease future population growth so fewer individuals must be removed in the future to maintain abundance within desired range (Garrott 1991, Gross 2000, Bartholow 2007, de Seve and Boyles Griffin 2013, Garrott and Oli 2013, Fonner and Bohara 2017, Garrott 2018); this approach has been adopted by the BLM to guide their overall strategy for horse management (BLM 2020). While this conceptual model provides an evidence-based strategy for managing horses within target population size ranges, resistance to management actions remains strong from various stakeholder groups.

Decisions related to horse management are complex and numerous factors are involved, including the form of management actions (i.e., types of management actions used; e.g., removal, fertility control, or compound alternatives involving multiple actions), management action magnitude (e.g., the relative number of individuals that are removed or treated), management frequency (e.g., varying management return interval), and management context (i.e., the degree to which the population exceeds target population size ranges). Managers could benefit from decision-support models that fully evaluate how the form, magnitude, frequency, and context of management alternatives influences the achievement of explicit objectives of diverse stakeholders in horse management.

Here, we used a stochastic, age-based matrix population model to explore how a wide range of management alternatives might influence horse populations and achieve multiple objectives of stakeholders. We used two scenario analyses to compare alternatives: a small set of 15 management scenarios varying in management form and magnitude, and a more exhaustive set comprising 1372 scenarios varying in management form, frequency, and magnitude simulated under five conditions of starting population size. To infer which scenario is most effective for maximizing stakeholder objectives, we evaluated scenario performance using a weighted utility function (i.e., objective function) that measured the relative reward of each scenario for achieving four fundamental objectives: ecosystem health objective, horse health objective, horse behavior objective, and management cost objective. While we did not consider all stakeholder values that may exist in reality, our analysis provides a framework for decision makers that identifies management strategies that accounts for diverse stakeholder objectives in a clear and transparent fashion.

Methods

Stakeholder objectives

We identified four objectives that represent important values of various stakeholders related to feral horse management (Table 1, Figure 1; Carlisle and Adams in press). The 'ecosystem health objective' seeks to maximize the health of natural ecosystems where horses occur; this objective is based on evidence in the literature that excessively large horse populations exert negative effects on sympatric wildlife and cause overall ecosystem degradation (National Research Council 2013, Davies and Boyd 2019). This objective is also stated in the 1971 Wild and Free-Roaming Horses and Burros Act, which articulates that management should promote a "thriving natural ecological balance" between horses and natural ecosystems on public lands where they occur (Public Law 92-195). Management that supports this objective will seek to reduce populations to be within target population size ranges (e.g., AML); this objective can be assessed by the size of the population after management has been performed or an average population size observed over the course of management.

The second objective is the 'horse health objective' which seeks to maximize the health of feral horses by ensuring they have ample resources (e.g., forage, water). The number of horses in a population after management can be used as a metric to assess horse health, assuming a linear relationship between herd size and horse health where smaller populations with greater *per capita* resources have higher health relative to larger populations with fewer resources (Choquenot 1991). If horse population density becomes so large as to potentially cause resource limitation for horses, managers might seek to reduce population size to be within target population size ranges (e.g., AML) and increase horse health.

The third objective is the ‘horse behavior objective’. Because management can be viewed as disruptive to natural horse behavior and social groups within populations (e.g., King et al. 2022), the ‘horse behavior objective’ seeks to minimize the amount of management performed in a population. The number of horses gathered, removed, and treated with fertility control can be used as metrics to assess the ‘horse behavior objective’.

Lastly, the ‘management cost objective’ seeks to minimize the cost of management incurred by managers. Because financial resources are limited and management actions (e.g., gathers, removals, fertility control treatment) can be expensive (Garrott 1991, de Seve and Boyles-Griffin 2013), management decisions might seek to minimize costs incurred by management. Here, we view the number of horses gathered, removed, and treated in a population as metrics for the management cost objective.

Objective function

To account for multiple competing stakeholder objectives, we built a weighted multi-attribute objective function to estimate the total combined utility (reward) accrued from n different objectives by an alternative relative to all other alternatives simulated (i.e., the weighted-sum method; Williams and Kendall 2017). Specifically:

$$R = w_1 u_1 + w_2 u_2 + \ldots + w_n u_n, \tag{1}$$

where R is the total reward for a given management alternative, u is the relative utility of a management outcome on a common scale (between 0 [worst] and 1 [best] among all scenarios), and w are objective weights that indicate the relative importance of each objective ($\sum_{i=1}^{n} w_i = 100$). For each scenario, we ranked objective metrics from worst to best relative to metrics in all scenarios (i.e., relative utility), rescaled from 0 (worst) to 1 (best), and then multiplied ranking by the objective weight for that metric. In general, we sought to assign equal weight to each fundamental objective in the reward function (25 points per objective; 100 total) and identified four metrics (mean population size, total number of horses gathered, total number of horses removed, total number of horses treated) that could serve as proxies for stakeholder values expressed by objectives while estimating scenario performance. However, all metrics contributed to more than one fundamental objective; therefore, we assigned weights to each metric such that the sum of each metric's weight equaled their contribution to weighted fundamental objectives. For example, we weighted the mean population size metric at 50 points, because we used it as the sole proxy for two fundamental objectives (25 points each). Similarly, we assigned metric weights of 16.6 points to the other three metrics, because each of these three metrics comprises one-third contributions to two fundamental objectives (i.e., $\frac{1}{3} * 25 + \frac{1}{3} * 25 = 16.6$; Figure 1). For each scenario, we summed weight-adjusted utility scores from all metrics to calculate an overall reward score.

Predictive model

To estimate the utility of different management alternatives on horse populations, we simulated how management alternatives influenced objectives using an age-based, two-sex, post-breeding census matrix population model (i.e., Leslie model; Leslie 1945) with 21 ages for each sex: one age for each year from 0–20 years old, and then a final age stage for all individuals ≥20 years old. To incorporate age-specific demographic rates, we built six demographic matrices that specified different survival and reproductive rates of feral horses observed during studies of populations across western North America, including at the Pryor Mountains, Montana (Garrot and Taylor

1990, Jenkins 2002, Roelle et al. 2010) and Garfield Flat and Granite Range, Nevada (Berger 1986, Jenkins 2002). Five of the matrices yielded mean population growth rates (λ) ranging from 1.066–1.178, while one matrix described high-mortality demographic conditions that can occur during uncommon extreme weather events, such as blizzards, that yield population declines ($\lambda < 1$). However, a global review of feral horse population dynamics (Ransom et al. 2016) suggested that λ for feral horses tends to be 1.18 but can vary from 0.84–1.39. Given the great range of potential λ values for feral horses that can occur in nature, we built four additional matrices that approximated conditions toward the upper range of potential λ values, which could yield λ of 1.19–1.32. To project populations through time, the model multiplied demographic matrices by a vector of age-structured abundance in each time step (year). Age-structured abundance was initialized by multiplying an estimate of true total population size by a vector of the average percent of a population belonging to each age class, based on observed age-based population structure data from field studies in Nevada, Montana, and Oregon (Berger 1986, Jenkins 2002).

The model projected populations using both deterministic and stochastic projection functions and assumed that feral horse populations have λ of 1.18 (i.e., 18% increase in population size per year; Ransom et al. 2016). We created a vector of probability values associated with the ten demographic matrices, where each matrix was assigned a weighted probability value and the sum of the product of each matrices' λ value and its weighted probability generated a mean $\lambda = 1.18$. For deterministic projections, we projected the population using each of the ten demographic matrices, and then used the probability weights for each matrix to generate a weighted average estimate for predicted future population size, again assuming $\lambda = 1.18$. For stochastic projections, we performed 50 replicate projections and used the weighted probability values to randomly draw a demographic matrix during each time step within each replicate. We did not include an element of density dependence in the model, because no studies have estimated density-dependent limits on horse population growth in the western United States.

The population model was built to simulate four management actions: removals, PZP-22 treatment, removals with PZP-22 treatment, and a null scenario of no management. We modeled removals whereby if populations exceeded maximum AML during designated removal years, individuals in a population are gathered and managers selectively remove more females than males from among gathered horses, such that non-removed individuals being returned to the range are male-biased (7 males:3 females), which is a commonly used BLM management practice to reduce future reproduction in the population (Bartholow 2007, Garrott 2018). We assumed that 75% of the total true population size is collected during a gather, and that individuals are removed to reduce the total population size to a target population size. Depending on scenarios, we modeled target population size as fixed at the midpoint between minimum and maximum AML (hereafter, AML midpoint) or a time-varying, stepwise value that started above maximum AML and decreased with each year to reach the AML midpoint in the final year of the projection. This former, fixed target population size caused larger initial removals when populations greatly exceeded AML followed by smaller removals in subsequent years (i.e., front-loaded removals), while the latter, time-varying target population size caused steady, smaller-magnitude removals over projection intervals.

We modeled PZP-22 treatment where individuals are collected during a gather, females ≥1 year-old are eligible to receive vaccine, individuals are treated, and then all individuals are released back into the population. We modeled different scenarios of vaccine treatment, where vaccine could be given to half or all age-eligible females and treated females could receive one dose or two (i.e., a ‘booster’). Vaccine-treated females were then subject to different reproductive rates than untreated females, depending on the total number of doses received and the number of years since their last dose.

We modeled the ability of PZP-22 treatment to decrease reproductive rates of individuals by first translating results from Rutberg et al. (2017) into estimates of effectiveness of preventing pregnancy and second incorporating a stochastic batch effect where random variation in batch effectiveness in a given year was modeled with a randomly drawn value between the minimum and maximum effectiveness of having received one dose, two doses, or three doses and the number of years since the last dose: 33–72% one and 20–40% two years after receiving a primer; 68–85% one, 70–75% two, and 60–72% three years after receiving a booster; and 78–95% one, 80–85% two, and 70–82% three years after receiving an additional booster. Because treatment with another immunocontraceptive vaccine caused an increase in survival in addition to decreases in reproduction (Kirkpatrick and Turner 2007), we assumed that PZP-22-treated females would experience similar increases in survival rates (1.02 times the baseline, untreated age-specific survival rate; not to exceed survival probability of 1 in any year) relative to untreated individuals. We modeled removals together with PZP-22 treatment when a gather is performed, non-PZP treated individuals are removed to meet population size targets, and then the remaining gathered eligible females are treated with PZP-22; previously PZP-22 treated females are not removed but are instead a priority for retreatment.

We built the model in the statistical program R (R Core Team 2020). We used the package ‘popbio’ (Stubben and Milligan 2007) to project populations during stochastic projections. The R code is provided in a USGS software release (Folt et al. 2022).

Scenario analysis

To explore how our multiple-objective utility function could support decisions for horse management, we developed 15 management scenarios to simulate with the model, compare outputs, and estimate performance (Table 2). Six scenarios were single-element scenarios that involved either removals or PZP-22 treatment and varied in the magnitude of removals (fixed or decreasing target population size) or PZP-22 treatment (treat half or all eligible females; treat with 1 or 2 doses). Eight scenarios were compound alternatives involving both removals and PZP-22 treatment in varying magnitude. We also included a null model of no management.

We simulated a hypothetical population with a starting population size (N_i) of 724 individuals with an AML of 200–333 individuals and projected the population for ten years under each of the 15 scenarios. For removal scenarios with fixed target population size, we specified a target population size of 267 individuals (i.e., the AML midpoint) that was constant across the projection. This setting caused the first removal to be a high-magnitude removal that quickly reduced population size to within AML; subsequent removals were only performed when the population exceeded maximum AML and were smaller. This created a scenario of high-magnitude removals early in the projection, followed by smaller removals when necessary (i.e., ‘front-loaded’ removals). For removal scenarios with decreasing target population size, we specified a target population size of 534 individuals in year 1 that decreased stepwise each year to 267 in year 10. This caused each removal to be of smaller, constant magnitude, such that small, steady removals worked together to achieve AML by the end of the projection (i.e., small, steady removals, or low-magnitude removals).

We simulated a management schedule where management was performed at the start of years 1, 4, 7, and 10 of the projection (i.e., a 3-year return interval on gathers and management). We measured the mean population size and tallied the total number of individuals gathered, removed, and treated over the projection interval. We used the objective function to calculate the cumulative reward of each scenario relative to the other 14 scenarios.

While conducting analyses and comparing outcomes of the 15 scenarios, we noted greater reward when management involved both removals and PZP-22 treatment and with a high-magnitude removal early during the management interval relative to other scenarios. Because there are many ways in which managers could structure management activities temporally (i.e., years that management actions are performed) and many contexts in which management might be used (i.e., variation in starting population size), we added a second scenario analysis to more fully evaluate how variation in the form, magnitude, frequency, and context of management alternatives influences the achievement of multiple objectives for horse management. To this end, we created a more exhaustive set of management scenarios that varied by 1) the management actions being used, 2) management frequency, 3) removal magnitude, and 4) PZP-22 treatment magnitude (Supplementary Table 1; Folt et al. 2022). Using the target population size range of (i.e., AML) of 200–333, we considered four types of management: removals, PZP-22, removals and PZP-22, and no management. For scenarios with removals, we considered nine schedules for years in which removals could be performed if populations exceed the maximum target population size: removals before the first year and every other year thereafter, every third year thereafter, and every fourth year thereafter; removals before the second year and every other year thereafter, every third year thereafter, and every fourth year thereafter;

removals in years 1 and 3, years 1 and 4, and years 1 and 5. We note that removals are only performed if population size exceeds the maximum target population size range, so removal schedules are a suggestion rather than a fixed summary of what happens during management.

To assess the effect of removal magnitude, we developed three scenarios; 1) low-magnitude removals, where the target population size started at two thirds of the difference between initial population size and AML midpoint (267 horses) and then decreased each year until it reached the AML midpoint in the last year, 2) medium-magnitude removals, where the target population size started at one third of the difference between initial population size and the AML midpoint and then decreased each year until it reached the AML midpoint in the last year, and 3) high-magnitude removals, where removals sought to reduce populations to a fixed target population size at the AML midpoint during each year of the projection. For scenarios with PZP-22 treatment, we considered 12 schedules for years in mare treatment with PZP-22: treatment before the year 1 and every other year thereafter, every third year thereafter, and every fourth year thereafter; treatment before year 2 and every other year thereafter, every third year thereafter, and every fourth year thereafter; treatment before year 3 and every other year thereafter, every third year thereafter, and every fourth year thereafter; and treatment before years 1 and 3, years 1 and 4, and years 1 and 5.

To assess the effect of PZP-22 treatment magnitude, we considered two factors: the proportion of age-eligible mares to be treated (half or all) and whether treated females would be kept in short-term holding to receive a booster treatment before being released (no, yes). We created 1372 scenarios that comprised all subsets of management form, frequency, and magnitude from these management factors (Supplementary Table 1). We then used the model to simulate each scenario under five contexts varying in initial population size (N_i): within AML (e.g., AML midpoint; $N_i = 267$ horses), maximum AML ($N_i = 333$ horses), 50% above AML ($N_i = 500$ horses), 100% above AML ($N_i = 666$ horses), and 200% above AML ($N_i = 999$ horses). For scenarios where N_i equaled the AML midpoint, we used the same removal magnitude targets as when N_i equaled the maximum AML; this allowed us to evaluate different removal strategies for when populations were already within AML (high, medium, low) and also facilitated an even number of scenarios across population size contexts. In total, this process yielded 1372 scenarios for each N_i, yielding a total of 6860 scenarios. We simulated each scenario using 25 replicates to quicken run times. We used the objective function to calculate the relative reward of each scenario and infer the most effective management scenario for different starting population sizes. We considered scenarios within 0.1 reward of the best-performing scenario to be equivocal in reward.

An important part of a decision process is to evaluate tradeoffs between performance of competing objectives across alternatives. For the objectives articulated here, the ecosystem health and horse health objectives likely trade off in performance with the horse behavior and management cost objectives, because, in general, excessive minimization of management aimed at achieving behavioral and cost objectives would fail to control horse populations and thus cause poor performance in ecosystem health and horse health objectives.

To understand tradeoffs, we used projection outcomes from the 1372 scenarios and visualized two indices that each represented a pair of the objectives. First, we used the mean predicted population size over the projection interval for each scenario to represent achievement of the ecosystem and horse health objectives, assuming that outcomes with a smaller average population size (i.e., within target population size range) yield a healthier ecosystem and higher horse health relative to larger populations with more grazing and less food availability. Second, to represent the horse behavior and management cost outcome, we used the objective function (above) to calculate an index of total management effort (hereafter, management index) for each of the 1372 scenarios at five levels of starting population size. We used the same objective function as described above, except for two differences: we excluded metrics related to population size, and then subtracted the resulting value from 50. This resulted in an index ranging from 0 (minimum) to 50 (maximum), where smaller values indicated stronger outcomes for the horse behavior and management cost objectives (i.e., relatively less effect of management on horse behavior and less total management cost). We illustrated trade-offs between objectives by graphing the relationship between population size and the management index that were predicted for scenario alternatives at five levels of starting population size. We identified and graphed the Pareto optimal frontier (Converse 2020) among scenarios at each starting population size, which indicated the scenarios with the greatest predicted value for the management and cost objectives for any given outcome of the ecosystem and horse health objectives among all scenarios simulated.

Results

Simulation of 15 management scenarios found compound alternatives involving both removals and PZP-22 treatment to outperform other alternatives (Table 2). Specifically, a scenario with high-magnitude removals to AML and two doses of PZP-22 treated to all age-eligible females during management years (scenario 14) reduced the population by 57.2% and yielded the highest reward from across all objectives (77.8). This strategy caused the lowest predicted estimates of mean population size (375), total number gathered (1416), and total removed (775) among all scenarios, but while treating a considerable number of females (358). Alternatively, single-action scenarios with PZP-22 treatment alone had the lowest reward (21.1–32.2; Table 2). These scenarios performed poorly because they failed to control population size (148–319% increases in population size) while also requiring relatively large numbers of individuals to be gathered and treated.

Simulation of 1372 scenarios each at varying N_i found consistent support for management with biannual high-magnitude removals and two years of PZP-22 treatment (half of age-eligible females treated with two shots in years 1 and 5) to maximize utility reward (Table 3). However, the timing and frequency of PZP-22 treatment in the best scenario varied slightly by N_i: when N_i began at the AML midpoint, biannual removals with PZP-22 treatment in years 3, 5, 7, and 9 achieved the greatest utility reward. Each of the most rewarding scenarios involved high-magnitude removals, which aimed to reduce populations to a target population size at the AML midpoint that was fixed through time.

We observed a strong tradeoff between metrics describing two pairs of objectives: the ecosystem and horse health objectives and the horse behavior and management cost objectives. Scenarios with a low management index that performed well for the horse behavior and management cost objectives tended to yield outcomes with relatively large populations that performed poorly for the ecosystem and horse health objectives; alternatively, scenarios with a relatively large management index resulted in low population size (Figure 2). However, scenarios with the greatest reward (Table 3) struck a balance along the Pareto optimal frontier by managing population size to be at or near target population size while minimizing total management, relative to other scenarios of comparable population size outcomes (Figure 2).

Discussion

Natural resource managers in the western United States are tasked with managing feral horse populations that experience rapid population growth rates and often exceed target population sizes (Garrott 2018). This challenging situation is exacerbated because the horse management topic has diverse and passionate stakeholders, who often have divergent perspectives and priorities related to horses and public lands use (Hurwitt 2017, Scasta et al. 2018, Scasta 2019, Carlisle and Adams in press) and may not support management decisions if they feel decisions are made without accounting for their interests (e.g., in the absence of stakeholder engagement; Voinov and Bosquet 2010, Gregory et al. 2012, National Research Council 2013).

We developed a decision-support framework that used a weighted objective function to evaluate the relative utility (i.e., reward) of management alternatives for maximizing four fundamental objectives of different stakeholders in horse management. Simulation of thousands of management scenarios varying in management form, frequency, magnitude, and context demonstrated that management with biannual removals and two years of PZP-22 treatment of half of females with two doses was, in general, the best approach to achieve stakeholder objectives during management of feral horse populations over a 10-year period, compared to other simulated alternatives. While the timing and magnitude of PZP-22 treatment during this optimal scenario varied slightly depending on context of initial population size, biannual removals that reduced population size to the AML midpoint with at least two PZP-22 treatment years maximized management reward because such scenarios struck a balance between competing objectives in the system and resulted in small populations (near or within AML) that required relatively few horses to be gathered, removed, and/or treated relative to other scenarios. While these results are consistent with previous horse modeling studies that suggested management with both removals and fertility control treatment provide an efficient means to achieve target population sizes (i.e., AML) and minimize cost (e.g., de Seve and Boyles-Griffin 2013, Fonner and Bohara 2017), our conceptual and mathematical framework explicitly accounted for the objectives of diverse stakeholders – including values and objectives related to animal welfare and behavior in addition to ecosystem and cost objectives – and inferred context-dependent management alternatives that maximized those objectives.

The BLM recently described their broad-scale management strategy for feral horse and burro populations on federal lands (BLM 2020). The BLM plan involves substantial investment in large removals to first reduce population size over the next five years followed by subsequent fertility control treatment and smaller removals to stabilize population growth and maintain population size within AML over the next 5–15 years. Our modeling results were largely consistent with this strategy, because (1) high-magnitude removal scenarios that reduced populations to the AML midpoint outperformed lower-magnitude removal scenarios at managing populations within target population size ranges, and (2) high-magnitude removals followed by PZP-22 treatment and small removals (when necessary) in subsequent years (Garrott 2018) were the top-performing scenarios across multiple population contexts. While the report describing the overarching BLM management strategy (BLM 2020) does not explicitly indicate how their broad-scale strategy accounts for the diverse objectives of different stakeholders, it appears consistent with alternatives in our scenario analysis that performed well at maximizing two key objectives of horse advocacy groups (maximizing horse health, minimizing negative effects of management on horse behavior and social structure), in addition to ecosystem and management cost objectives.

Making management decisions in the face of multiple, competing objectives benefits from a collaborative approach, where appropriate stakeholders are engaged, their values are understood, and clear objectives are developed from those values (Converse 2020). Stakeholder engagement early in the decision process can pay dividends down the road when the decision is implemented, because stakeholders are more likely to understand the problem, see that their views and concerns have been incorporated in the decision process, and therefore are more likely support the decision (Voinov and Busquet 2010, Gregory et al. 2012). While we did not directly engage outside stakeholders here and the objectives applied in our model do not represent all the diverse stakeholder groups, values, and objectives that exist in reality (Carlisle and Adams in press), we thought carefully about the challenge of managing horse populations and attempted to view horse management from more than just the perspective of managers when identifying values and developing objectives to be maximized by management decisions. We believe our approach provides a useful demonstration of how multiple, competing objectives can be incorporated into the decision process for horse management with a simple objective function that infers relative reward of management alternatives. Further work could strengthen support for management decisions by more fully engaging the diversity of horse management stakeholders in a more direct and transparent fashion, such as with a structured decision-making approach (Gregory et al. 2012, Runge et al. 2020).

Our approach considered four fundamental objectives and treated each with equal weight during our decision-support process; however, federal law under the Wild and Free-roaming Horse and Burro Act mandates that populations must be managed for a sustainable balance between horses, wildlife, and additional uses of landscapes where horses occur (Public Law 92-195). Therefore, the objectives we considered here might benefit from an altered weighting system and/or a revised objectives hierarchy altogether, to place greater emphasis on the law-mandated ecosystem and horse health objectives (Public Law 92-195). To this end, future decision-support efforts might seek to clarify the true fundamental objectives of horse management, particularly as they relate to federal law (i.e., Public Law 92-195), and make revisions to our conceptual approach, objective function, and objective weights, such that the decision process would more accurately reflect law-mandated objectives in addition to a full suite of stakeholder values and objectives (Carlisle and Adams in press). For example, additional stakeholder values and objectives could be incorporated into the framework, or the objectives described here could be de-emphasized or removed.

We also recognize that numerous factors that influence policy decisions are not included in our analytical framework, such as capacity to carry out management in the field across large spatial scales. Future revisions to our model and decision-support framework might benefit from accounting for logistical constraints experienced by management agencies in the field or in holding facilities, so that management actions being evaluated are realistic and achievable at larger regional scales. Last, future work might revise how performance is evaluated for different objectives, perhaps by including metrics specific to each objective so that additional trade-off relationships can be estimated, or by assuming non-linear relationships between metrics and objective performance.

Management implications

Management of feral horses is a daunting task because of rapid population growth rates, logistical challenges during management, and intense public interest and scrutiny of management. For management decisions to be more widely accepted by stakeholders, decisions could transparently account for the multiple objectives of diverse stakeholders and seek to strike a maximal balance between competing objectives. We presented a decision-support framework where management can be chosen based on explicit evaluation of diverse stakeholder objectives, including that of, for example, both resource managers and advocacy groups. Using an objective function that measured the overall reward of management alternatives for achieving different stakeholder objectives, our simulations of scenarios involving removals and/or PZP-22 treatment found support for one management scenario (removals to the AML midpoint followed by PZP-22 treatment and additional removals) that consistently maximized reward from four objectives across different contexts of initial population size prior to management. Our results suggest that, among the scenarios we considered for single-herd management, removals to the AML midpoint with subsequent fertility control treatment provides the quickest way to reduce a population to within target ranges, while also reducing the number of individuals that need to be gathered and removed during 10 years of management. Our results illustrate how diverse stakeholder values can be incorporated into the decision process for horse management with a simple objective function used to identify alternatives that increase the overall value of decisions for stakeholders.

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Table 1. Objectives that represent diverse societal values to be maximized (or minimized) during management of feral horse (*Equus caballus*) populations. Assessment metrics provide clear, measurable attributes to evaluate the performance of alternatives with respect to each objective. See Figure 1 for an influence diagram describing the relationship between management alternatives, objectives, and metrics.

Name	Objective	Rationale	Assessment metric
Ecosystem health objective	Maximize ecosystem health	If increasing horse population density causes negative effects on overall ecosystems, then management decisions might seek to prevent excessively large horse populations	The number of horses in a population can be used as a proxy for ecosystem health, which should be maximized when horse populations are within target population size ranges (i.e., AML)
Horse health objective	Maximize horse health	If high population density of horses causes resource limitation that drives decreased horse health, then management decisions might seek to prevent excessively large populations	The number of horses in a population can be used as a proxy for horse health, which should be maximized when populations are within target population size ranges (i.e., AML)
Horse behavior objective	Minimize effects on horse behavior and social structure	If gathers, removals, and treatments disrupt horse behavior and/or social structure, management decisions might seek to minimize the amount of management performed	The number of horses gathered, removed, and treated in populations can be used as a proxy for effects on horse behavior/social structure, which should be minimized
Management cost objective	Minimize the cost of management	Because resources are limited and management actions (gathers, removals, and treatments) are costly, management decisions might seek to minimize costs incurred by management	The number of horses gathered, removed, and treated in a population can be used as a proxy for cost, which should be minimized

Table 2. Results from a predictive population model for feral horses (*Equus caballus*) estimating the reward of 15 scenarios for achieving objectives in horse management over a 10-year projection interval. "Treat" refers to PZP-22 treatment to age-eligible females. Mean population size is the average population size over the entire projection; numbers gathered, removed, and treated are sums from over the entire projection. 'Reward is the utility of each scenario for achieving objectives relative to other scenarios.

Scenario Number	Management action	Management form	Final population size	% increase population size	Mean population size	Number gathered	Number removed	Number treated	Reward
1	No management	-	3647	403.7%	1792	0	0	0	46.7
2	Removals	Remove to AML	315	-56.5%	399	1537	959	0	63.3
3		Small removals	348	-51.9%	611	2200	1267	0	36.7
4	PZP-22	Treat half + 1 dose	3036	319.3%	1597	3747	0	762	21.1
5		Treat all + 1 dose	2530	249.4%	1439	3455	0	1430	28.9
6		Treat half + 2 doses	2623	262.3%	1456	3621	0	749	26.7
7		Treat all + 2 doses	1792	147.5%	1169	3351	0	1532	32.2
8	Removals + PZP	Remove to AML + treat half + 1 dose	318	-56.1%	397	1523	928	133	66.7
9		Small removals + treat half + 1 dose	360	-50.3%	608	2173	1224	234	36.7
10		Remove to AML + treat all + 1 dose	325	-55.1%	394	1494	888	333	67.8
11		Small removals + treat all + 1 dose	367	-49.3%	601	2115	1152	577	40.0
12		Remove to AML + treat half + 2 doses	314	-56.6%	390	1488	882	138	76.7

13	Small removals + treat half + 2 doses	354	-51.1%	594	2124	1158	238	44.4
14	Remove to AML + treat all + 2 doses	310	-57.2%	375	1416	775	352	77.8
15	Small removals + treat all + 2 doses	352	-51.4%	563	1963	947	611	48.9

Table 3. The three best-performing management scenarios (among 1372 alternatives) that maximized Reward for achieving multiple objectives of feral horse (*Equus caballus*) management for five conditions of initial population size (N_i) (6860 total scenarios). The worst-performing scenario is also included for comparative purposes. Simulation outcome metrics are an average (mean population size) or a sum (number gathered, number removed, number treated) across the entire projection. Removals are only performed during removal years if the population size exceeds the upper limit of AML (333 individuals). Levels for N_i are: AML midpoint (267), max AML (333), 50% above AML (500), 100% above AML (666), and 200% above AML (999).

Ni	Management form	Removal year	Removal magnitude	PZP-22 frequency	PZP-22 magnitude	Final population size	Final % above AML	Mean population size	Number gathered	Number removed	Number treated	Utility reward
AML midpoint	Removal + PZP-22	1 3 5 7 9	High	3 5 7 9	Treat half + two doses	354	6.3	332	1098	350	174	80.6
	Removal + PZP-22	1 3 5 7 9	High	3 7	Treat half + two doses	361	8.4	337	1084	389	79	80.5
	Removal + PZP-22	1 3 5 7 9	High	3 7	Treat half + two doses	360	8.1	337	1087	394	80	80.1
	PZP-22	-	-	2 4 6 8 10	Treat half + one dose	1095	228.8	605	2247	0	500	19.6
Max AML	Removal + PZP-22	1 3 5 7 9	High	1 5	Treat half + two doses	413	24.0	347	1127	423	69	82.7
	Removal + PZP-22	1 3 5 7 9	High	3 7	Treat half + two doses	369	10.8	343	1303	439	87	81.9

	Removal + PZP-22	1 3 5 7 9	High	1 5 9	Treat half + two doses	396	18.9	345	1173	422	114	81.2
	PZP-22	-	-	2 4 6 8 10	Treat all + one dose	926	178.1	607	2258	0	1071	18.7
50% above max AML	Removal + PZP-22	1 3 5 7 9	High	1 5	Treat half + two doses	402	20.7	360	1422	597	66	87.2
	Removal + PZP-22	1 3 5 7 9	High	3 7	Treat half + two doses	370	11.1	357	1451	611	80	86.7
	Removal + PZP-22	1 3 5 7 9	High	1 3	Treat half + two doses	395	18.6	362	1420	633	64	85.7
	Removal + PZP-22	2 6 10	Low	1 5 9	Treat all + one dose	513	54.1	575	2964	960	610	9.9
100% above max AML	Removal + PZP-22	1 3 5 7 9	High	1 5	Treat half + two doses	411	23.4	375	1560	767	53	88.1
	Removal + PZP-22	1 3 5 7 9	High	3 7	Treat half + two doses	362	8.7	373	1593	784	83	87.5
	Removal + PZP-22	1 3 5 7 9	High	1 5 9	Treat half + two doses	396	18.9	375	1562	761	102	87.5
	Removal + PZP-22	2 6 10	Low	1 5 9	Treat all + one dose	693	108.1	755	3886	1305	808	5.9
200% above max AML	Removal + PZP-22	1 3 5 7 9	High	1 5	Treat half + two doses	416	24.9	405	1763	1098	33	89.5
	Removal	1 3 5 7 9	High	-	-	385	15.6	405	1785	1141	0	89.2
	Removal + PZP-22	1 3 5 7 9	High	1 5 9	Treat half + two doses	387	16.2	404	1759	1111	72	89.1

Removal + PZP-22	2 6 10	Low	1 5 9	Treat all + one dose	941	182.6	1050	5452	1866	1143	5.3

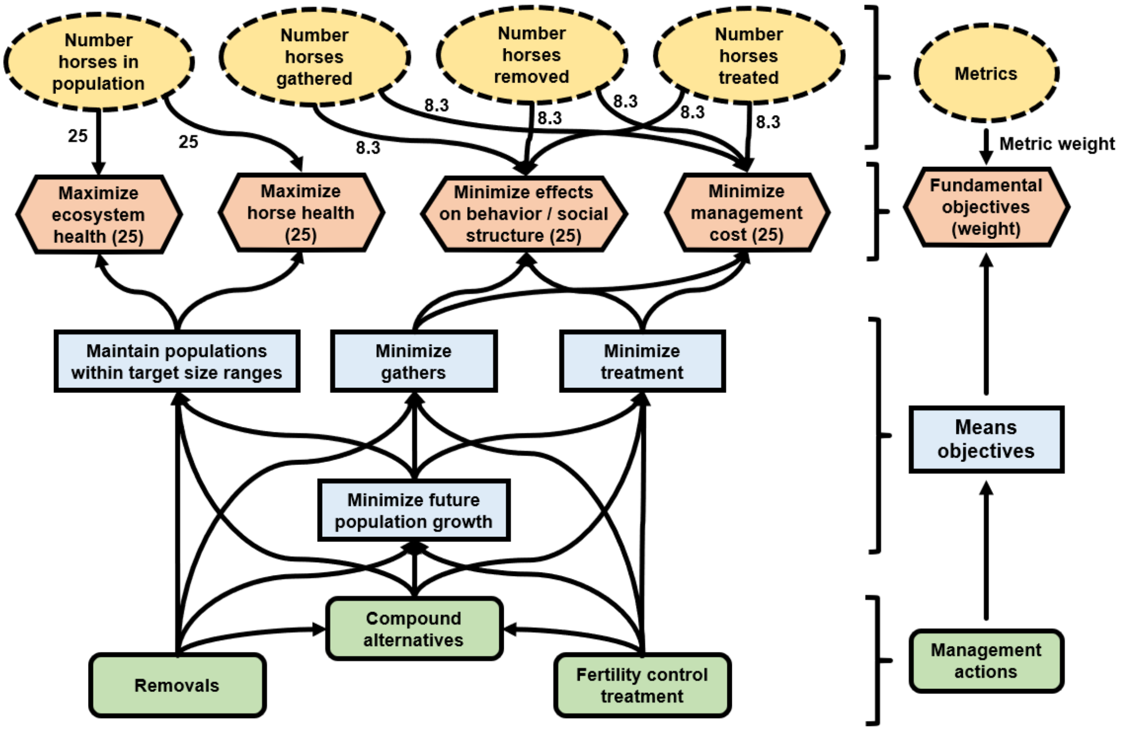
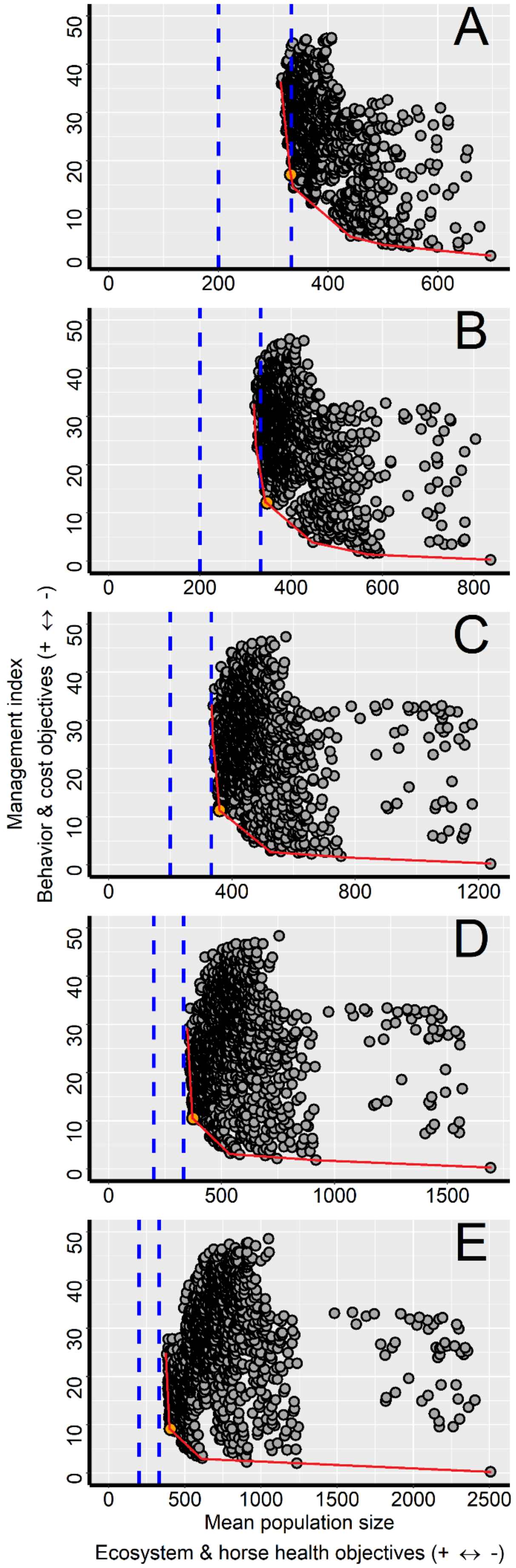


Figure 1. Influence diagram describing how management actions (green rounded rectangles) influence means objectives (blue rectangles) and, ultimately, fundamental objectives of stakeholders (orange hexagons) during management of feral horse (*Equus caballus*) populations. The performance of management alternatives for achieving fundamental objectives can be assessed by performance metrics (yellow dashed circles) using a weighted, multiple-objective utility function. Numbers indicate weights for fundamental objectives (numbers in hexagons) and metrics (numbers next to arrows); the sum of metric weights contributing to a fundamental objective equals the weight of the fundamental objective.


A
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500
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1500
2000
2500
Management index
Behavior & cost objectives (+ ↔ -)
Mean population size
Ecosystem & horse health objectives (+ ↔ -)

Figure 2. Pareto efficiency frontiers illustrating the tradeoff between ecosystem and horse health objectives (x-axis; as measured by mean population size) and horse behavior and management cost objectives (y-axis; as measured by a management index) from simulations of 1372 alternative management scenarios (grey points) for feral horse (*Equus caballus*) populations. Panels (A-E) indicate simulations varying in starting population size (N_i) relative to appropriate management levels (AML; 200–333 horses; blue vertical dashed lines): (A) within AML ($N_i = 266$ horses; i.e., AML midpoint), (B) maximum AML ($N_i = 333$ horses), (C) 50% above maximum AML ($N_i = 500$ horses), (D) 100% above maximum AML ($N_i = 666$ horses), and (E) 200% above maximum AML ($N_i = 999$ horses). Lower values for each axis represent outcomes that better accomplish objectives (+) relative to higher-scoring values (-). Solid red lines represent the Pareto efficiency frontier of non-dominated solutions (solutions with the highest-value outcome on the y-axis for any predicted outcome on the x-axis), and the orange point indicates the most rewarding alternative estimated by a multiple-objective utility function.

Supplementary Table 1. Factors used to create 6860 management scenarios simulated by the model (Folt et al. 2022) for populations varying in starting population size (N_i) relative to the target population size range, hereafter referred to as Appropriate Management Levels (AML). The factors in the first six columns were used to create 1372 scenarios varying in management action, removal year, removal target, PZP-22 treatment year, PZP-22 treatment magnitude (proportion treated and whether treatment involved a booster). The 1372 scenarios were simulated at each of five starting population sizes – the AML midpoint (267 horses), AML maximum (333 horses), 1.5*AML maximum (500 horses), 2*AML maximum (666 horses), and 3*AML maximum (999 horses) – which yielded 6860 total scenarios. [1]For removal magnitude, we calculated (1) high-magnitude removals as fixed at the AML midpoint in each year; (2) the medium-magnitude removal target as the AML midpoint plus 1/3 the difference between Ni and the AML midpoint in year 1; this target then decreased each year until it reaches the AML midpoint in year 10; and (3) the low-magnitude removal target as: the AML midpoint plus 2/3 the difference between Ni and the AML midpoint in year 1; this target then decreases each year until it reaches the AML midpoint in year 10.

Management actions	Removal Years	Removal target population size[1]	PZP-22 Years	Proportion of mares PZP-treated	PZP-22 booster	N_i
No management	Every other year; starting in year 1	High-magnitude removals	Every other year; starting in year 1	Half of age-eligible horses	No	AML midpoint
	Every third year; starting in year 1	Medium-magnitude removals	Every third year; starting in year 1	All of age-eligible horses	Yes	AML maximum
Removals	Every fourth year; starting in year 1	Low-magnitude removal	Every fourth year; starting in year 1			1.5 * AML maximum
	Every other year; starting in year 2		Every other year; starting in year 2			2 * AML maximum

PZP-22	Every third year; starting in year 2	Every third year; starting in year 2	3 * AML maximum
	Every fourth year; starting in year 2	Every fourth year; starting in year 2	
Removals and PZP-22	Years 1 and 3	Every other year; starting in year 3	
	Years 1 and 4	Every third year; starting in year 3	
	Years 1 and 5	Every fourth year; starting in year 3	
		Years 1 and 3	
		Years 1 and 4	
		Years 1 and 5	

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