Estimating Mountain Lion Abundance in Arizona, 2003-2016

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INTRODUCTION

One of the most challenging aspects of mountain lion (*Puma concolor*) management is that abundance and density are difficult to estimate because of their elusive behavior, solitary nature and propensity for nocturnal movements. In Arizona, their distribution in rugged terrain and wide dispersal across the state make them a difficult population to study at large spatial scales. The high cost of field-intensive, long-term research projects is another limitation, making efforts to count every mountain lion logistically impractical or economically prohibitive. As an alternative to direct counts, indices and noninvasive sampling are widely used as alternative methods to survey mountain lion populations. Track counts, remote cameras, and genetic analysis of scats have been used to estimate local abundance in Arizona (Germaine et al. 2000, Smythe 2008, Naidu et al. 2011), but there are limitations to extrapolating these estimates to the statewide population (Long et al. 2003, CMGWG 2005, Choate et al. 2006). Consequently, wildlife managers may use expert opinion, numbers of mountain lion sightings, depredation incidents, and harvest to assess population status and trend. However, these are not ideal methods for evaluating mountain lion populations because sighting reports can be unreliable and harvest information generally are not sensitive to small population changes over a short period of time (Martorello et al. 2006).

In Arizona, statewide mountain lion abundance and survival is poorly understood and studies of survival and abundance have been limited in scope and sample size. Given the shortcomings of indices and the desire for information on which to base management decisions, there is a need for reliable and affordable techniques to monitor population status and trends for mountain lions, especially for those in hunted populations (e.g., Anderson and Lindzey 2005). Currently, the Arizona Game and Fish Department (AZGFD) uses sex and age composition derived from harvested mountain lions to monitor population trends but modern analytical developments in wildlife science offer additional methods to interpret these data and assess the population (Gove et al. 2002, Skalski et al. 2005b). In this paper, we use statistical population reconstruction models of Fry (1949) and Gulland (1965) as reported by Skalski (2005a & b) using age-at-harvest data from 2004 through 2016 to estimate a range of abundance for mountain lions statewide.

Virtual population analysis (VPA), also known as cohort analysis, is an age-structured population reconstruction method that uses age-at-harvest data to reconstruct cohort abundance over time and sums across cohorts to estimate animal abundance (Skalski 2005b). VPA was first used in fisheries management where catch data are accessible but other traditional methods of abundance estimation are difficult to apply. More recently, age-structured population reconstruction models have been applied to a variety of mammals including mountain lions (Clawson 2010, Johnson 2017), black bear (Skalski 2005b), martens, (Skalski 2011), elk (Gove et al. 2002), moose (Ueno et al. 2009), and black-tailed deer (Skalski et al. 2005c).

METHODS

Data

Comment [MC1]: I divided "data" and "analysis" into sections, but maybe reconsider.

Comment [AH2]: Did we use tooth age data from 2003? I thought we started with 2004.

We used age-at-harvest data for mountain lions collected and maintained by AZGFD from 2003-2016. In Arizona, successful hunters are required to register harvested mountain lions within 10 days of harvest, at which time a premolar tooth is pulled. Tooth submission was voluntary from 2003-2005, but mandatory from 2006-2016. Age-at-harvest was determined using cementum annuli analysis (Matson's Laboratory, Manhattan, Montana). In addition, livestock operators are required to report depredation-related removals of mountain lions to AZGFD, although teeth are generally not collected from these animals. A smaller number of mountain lions are removed due to public safety concerns, and these are also reported to AZGFD. Mountain lions killed by vehicles, recovered from poachers, or otherwise encountered after death are intermittently reported to AZGFD. For this study, we constructed the age-at-harvest data solely from hunter-harvested, depredation-related, and public-safety removal mountain lions because they are consistently reported to AZGFD. We excluded other categories because they were not reliably reported and our analysis methods assume that harvested animals are reported accurately.

We also used mortality data from GPS-collared mountain lions to generate survival estimates. A total of 143 GPS collars were affixed to 137 animals by AZGFD, University of Arizona, U.S. Geological Survey, and National Park Service between July 2003 and October 2017 during several independent studies in Arizona. Animals were collared in 8 of 15 counties in Arizona. When a collar emitted a mortality signal, staff investigated and assigned a cause of death to the animal.

We also obtained estimates of natural mortality rates from literature published after 2000 covering hunted mountain lion populations in the Southwest USA. We used scientific search engines to locate peer-reviewed papers that provided estimates of natural mortality rates among wild populations of mountain lions. We excluded studies of non-hunted populations with the expectation that mortality rates would differ from those in Arizona. Similarly, we excluded studies from outside Arizona, southern California, Nevada, Utah, Colorado, New Mexico, and west Texas on the grounds that mountain lion mortality causes and rates could differ substantially in dissimilar habitats.

Analysis

We used a virtual population analysis to estimate abundance from age-at-harvest data and survival estimates, using methods developed by Gulland (1965). Essentially, the population is divided into harvest-mortality and natural-mortality animals, with the assumption that all harvest-mortality animals are reported to AZGFD, while natural-mortality animals are unreported. We can estimate abundance by summing the number of harvest-mortality animals, and then use survival estimates to inflate this tally to account for natural-mortality animals.

Comment [MC3]: Did we put a date limit on that too?

Comment [MC4]: More estimates out there if we go to theses and state reports.

Comment [MC5]: Or "harvest" and "non-harvest" or "reported" and "non-reported"

Comment [f6]: I see the idea of reported vs unreported, but I think I don't want to use "unreported" rather natural mortality for human dimension sensitivity reasons. We can discuss & I can give my rationale.

Under this approach, harvest data was organized into a year by age-at-harvest table. From 2004 to 2016, 74% of animals were aged, while in 2003, only 1.4% of animals were aged. We assumed that the unaged animals were a random sample of all animals, and therefore we completed the life table by assigning ages to the unaged animals according to the age distribution of the aged animals. We then summed harvest data within each cohort to obtain year- and age-specific abundance estimates.

Comment [AH7]: Should we insert the age-at-harvest table?

Comment [AH8]: Can we get this table? Do we want to include the table in the results?

For incomplete cohorts, it is necessary to estimate the number of animals alive in the most recent year (2016). To do this, we first estimated the harvest mortality rate for age class *j*,

$$\hat{M}_j = \sum_i h_{i,j} \Big/ \sum_i \hat{N}_{i,j}$$

where $h_{i,j}$ is the number of harvested animals in year *i* and age class *j*, and $\hat{N}_{i,j}$ is the estimated size of the cohort. For the incomplete cohorts, we then estimated cohort size using the known harvest data and the estimated harvest mortality rate, so that

$$\hat{N}_{last,j} = h_{last,j} \Big/ \hat{M}_j$$

where 'last' indicates the most recent year. Once cohort size is estimated for incomplete cohorts, abundance can be estimated by summing across cohorts within each year to obtain annual abundance of harvest-mortality animals. These abundance estimates are often termed minimum known population estimates, but in this case, we excluded known individuals with mortality types that are not consistently reported, such as vehicle collisions and poached animals. Thus, these abundance estimates are less than the minimum known population.

The above abundance estimates are clearly lower than the true abundance because they are based only on harvested animals. To account for this, we inflated the year by age-at-harvest table to account for non-harvested animals. For the oldest age class, we assume that total mortality is 1 and we inflate the harvest to estimate cohort size according to

$$\hat{N}_{i,old} = \frac{h_{i,old}}{\left(\dfrac{\mu_{H_{old}}}{\mu_{H_{old}} + \mu_N}\right)}$$

where 'old' indicates the oldest age class, μ_N is the instantaneous natural mortality rate, and μ_{H_j} is the instantaneous harvest mortality rate, which is estimated by $-\ln\left(1-M_j\right)$. It should be evident that a higher natural mortality rate yields a higher estimated cohort size. For all other age classes, $\mu_{H_{j-1}}$ is estimated (using numeric methods) from

$$\frac{N_{i,j}}{h_{i-1,j-1}} = \frac{\left(\mu_{H_{j-1}} + \mu_N\right)e^{-\left(\mu_{H_{j-1}}+\mu_N\right)}}{\mu_{H_{j-1}}(1-e^{-(\mu_{H_{j-1}}+\mu_N)})}$$

and $N_{i-1,j-1}$ is estimated from

$$N_{i-1,j-1} = N_{i,j}e^{(\mu_{H_{j-1}}+\mu_N)}$$

Again, the larger μ_N, the more that the counts of harvested animals need to be inflated to account for natural mortality, resulting in a larger estimated cohort size. Again, for incomplete cohorts, the number of animals alive in the most recent year must be estimated from harvest and natural mortality rates (see Skalski et al. 2005 for details). After generating year- and age-specific abundance estimates, annual abundance can be obtained by summing across cohorts.

Comment [MC9]: I could spell this out, but it gets tedious.

Comment [MC10]: The above could be shortened a lot just by referring to Skalski et al. 2005.

These calculations require that we have an estimate of the natural mortality rate. We obtained one estimate of the natural mortality rate from the 143 GPS collars deployed by AZGFD. We used a nest survival model to estimate daily survival rates for mountain lions (Johnson 1979, Rotella 2016). We then converted the daily survival estimate to an annual mortality rate and used this in the Gulland estimator described above. Because we were interested in natural mortality, we right-censored harvested animals, as well as capture mortalities and 26 animals removed to support a big-horn sheep reintroduction project. We estimated survival rates using the RMark package (Laake 2013) to interface with Program MARK (White and Burnham 1999) in Program R (R Core Team 2016).

RESULTS

Over 14 years, 3,976 harvest mortalities were reported to AZGFD. Considering only these harvested animals, the minimum known population has been relatively steady over the past 14 years, averaging 1,213 animals (Figure 1). However, this number excludes both a small number of reported mortalities due to vehicle strikes and poaching, and an unknown number of natural mortalities.

Using the nest survival analysis, we estimated that the annual natural mortality rate for 137 animals with GPS collars was 19.1% per year (SE = 3.6%). Using this value for μ_N in the Gulland estimator increased the estimate of the average population size to 2,451 (Figure 1). A review of published estimates of natural mortality rates yielded estimates between 9.0% and 18.0% (Table 1). We translated these into additional estimates of abundance (Figure 1).

Comment [AH11]: Matt, does the final product provide confidence intervals? Did you run a goodness of fit test?

Comment [AH12]: Should we insert the estimates of abundance by age-class and year?

DISCUSSION

The availability of age-at-harvest data makes age-structured population reconstruction methods appealing where traditional surveys are impractical. We believe our approach was useful for initial model development, and offers a foundation on which future modeling efforts can be built. While there are some limitations with using harvest only data, this estimate currently provides the best scientifically sound statewide estimate of abundance and will be useful in monitoring population status and trends. When paired with additional auxiliary information, the abundance estimate should become more reliable and precise. Our next step will likely involve the consideration of models that incorporate additional inputs such as reporting rates and hunter effort, and offer the potential to estimate additional parameters of interest such as survival rates, annual recruitment, and harvest probabilities. Though this model only uses one survival rate for both sexes and all age classes, we know that survival varies for males and females across age classes (Fecske et al. 2011, Ruth et al. 2011, Clark et al. 2014). Future models could apply sex-specific and age-specific survival rates to generate a more robust abundance estimate.

Comment [AH13]: Matt, can we get these from our current model?

The natural mortality rate in the annual mortality analysis for Arizona was higher than estimates we included from other southwestern states, however, it is consistent with natural mortality rates reported from Arizona (Table 1; Cunningham et al. 2001, McKinney et al. 2009). Although we produced abundance estimates using other natural mortality rates to show the likely range of abundance, we feel confident that the estimated abundance using Arizona natural mortality rates most likely represents mountain lion abundance statewide. We also believe the model to be reliable in predicting changes to the population because the observed decrease in abundance from 2006-2012 coincides with an increase in hunter harvest trends from 2005-2011.

MANAGEMENT IMPLICATIONS

Population reconstruction models provide a convenient and flexible framework for estimating abundance at large spatial scales, where rigorous surveys or long-term, expensive mark-recapture methods may not be practical. It also allows wildlife managers to monitor changes in abundance over time and predict population trajectory by estimating both past and present population abundance (Clawson et al. 2016). Hunter harvest data are easy to collect, relatively low cost, and can provide crucial information on survival, recruitment, sex and age composition, and abundance (Skalski et al. 2005). Population reconstructions methods can be used in conjunction with indices or radio-telemetry studies to refine the accuracy of abundance estimates and investigate the effects of management actions.

Virtual population analysis can be conducted annually, or any other desired length of time, incorporating current harvest data to update abundance estimates. It can be tailored to the specific harvest and auxiliary data that wildlife management agencies have available and can be used to evaluate and refine management approaches. In Arizona, VPA is currently underway to estimate abundance for newly proposed Mountain Lion Management Zones in which harvest thresholds will be set for each management zone based on abundance estimates in each zone.

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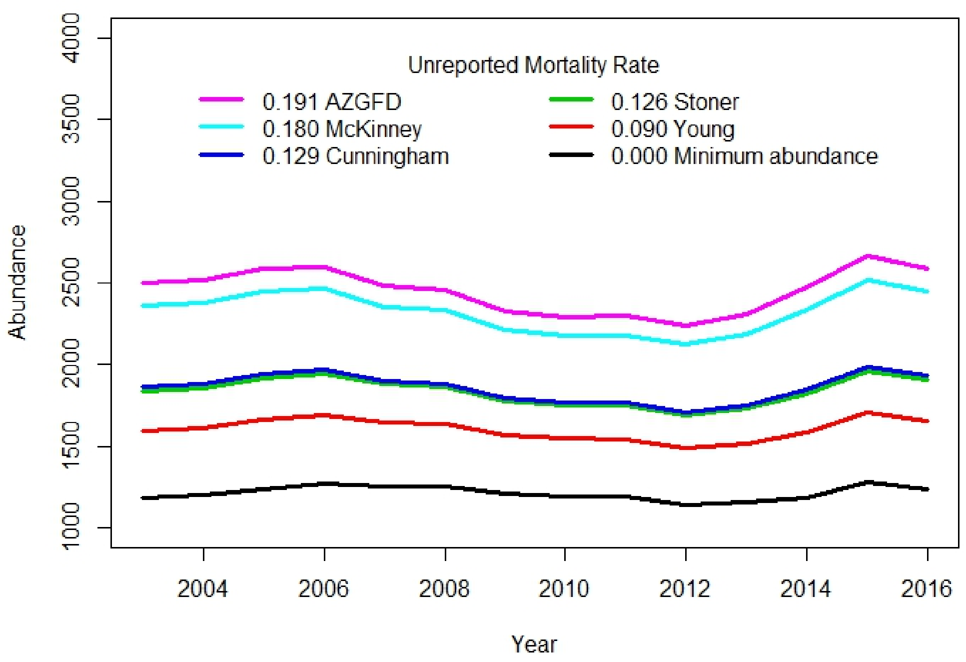
Table 1: Sources of estimates of natural mortality rates.

Source	Location	No. of lions	Natural mortality rate	Notes
Cunningham, et al. 2001	SE Arizona	24	12.9%	
Stoner et al. 2006	S-Central Utah	110	12.6%	We combined estimates from two study sites.
McKinney et al. 2009	N-Central Arizona	16	18.0%	We combined estimates from two study sites.
Young et al. 2010	W Texas and SE New Mexico	60	9.0%	We combined estimates from three study sites.

Figure 1: Estimated abundance of mountain lions (Puma concolor) in Arizona, 2003-2016.



Comment [AH14]: Stoner and Young rates have decreased from previous draft. Young from 0.170 to .090??? Can we double check those.