Elk Statistical Population Reconstruction Modeling:

Preface to the 2018 Proof-of-Concept Report

What is the purpose of this population modeling project?

Statistical models are used to estimate total abundance and other parameters of wildlife populations. These models are very helpful in better understanding and managing large populations because absolute counts (censuses) of animals are not possible for most wildlife species. Historically, Kentucky Department of Fish and Wildlife Resources (KDFWR) used a traditional Life-Table Model to produce scientific point-estimates for abundance (population number) of elk in the 16-county elk restoration zone, which encompasses about 4 million acres in southeastern Kentucky. The use of a new model provides opportunities to compare the point-estimate for total abundance from our traditional life-table model with the point-estimate from a new model, as well as to provide estimates of other population parameters. Statistical population reconstruction models have moved to the forefront in wildlife population modeling in the past decade, and are being used increasingly by universities and agencies for research and management of wildlife populations.

What is a Statistical Population Reconstruction (SPR) model?

SPR models are scientifically sound, robust computer models that are generated to estimate: age- and sex-specific abundances; harvest vulnerabilities; and survival through time. These types of models are considered by experts in the field to be the most rigorous, statistically valid population models currently available.

How should the model outputs be interpreted?

Wildlife biologists use statistical population models to produce *estimates* of animal population parameters. In virtually every situation in the wild, it is impossible to count (census) individual animals that comprise wildlife populations. This is due to a number of factors, such as geographic extent of populations, presence of structural cover that obscures or inhibits observations, mobility of animals, limited physical capacity or technology, temporal and physical constraints, etc. This fact has led to the development of many population estimation techniques, including computerized statistical modeling in recent decades.

Because different models use different statistical methodologies to produce estimates, their results are necessarily different. We must keep in mind that point-estimates for population parameters, such as total abundance, will vary depending on the model being used. For example, the traditional model that KDFWR used to estimate total elk abundance provided a 2016 point estimate of about 11,000 elk in southeastern Kentucky’s elk zone. By contrast, the SPR model yielded a point-estimate of total abundance of about 13,000 elk in in 2016. These estimates obviously differ in an absolute sense, but they are *statistically* comparable when taking into consideration the “confidence interval” generated by the SPR model. A confidence interval is a numeric range in which the model predicts the actual value of the population occurring, with a specified percent certainty (statistically speaking). The SPR model’s 95% confidence interval included the point-estimate generated by the traditional life-table model, indicating that the total abundance point-estimates are “statistically similar” or comparable in this case. Over time, with additional data collected and entered into the model, we expect the confidence intervals for the SPR model to continually narrow and the point-estimates to become more reliable because of more robust data sets. Note: These estimates should *NOT* be equated with absolute counts of animals (census results), because census of the elk population is impossible for aforementioned reasons. The most important take-aways from the models are *trends over time* in the estimates produced, which help us to evaluate the effects of management (such as seasons and bag limits) and recommend changes to produce desired results.

How does this elk population model differ from the model KDFWR has traditionally used?

The traditional model, what is known as a life-table model, utilizes many of the same data sources the SPR model uses. The greatest benefit of a life-table model is that it works very well in Kentucky’s situation because we know the initial population inputs, whereas most states don’t have that luxury. For example, we have records of all the elk that were released in Kentucky, including the sex and age of each animal brought here. If we combine that with other data sources (e.g., harvest rates, non-harvest mortality rates, reproductive rates, etc.) from Kentucky’s herds, we can track with relative accuracy the population’s growth through time. There are, however, two major drawbacks to the life-table model as we currently use it. Our current life table only produces point estimates (i.e., lack of confidence intervals), and it is not capable of utilizing additional sources of auxiliary data that the SPR model can use (e.g., hunter effort, age-at-harvest data, etc.), thus allowing for less predictive abilities. The SPR model is more robust, and allows biologists to incorporate more data, which results in more refined estimates. This is not meant to say that we should completely disregard the life-table model, because it certainly provides valuable trend information and a means to double check other estimates; it’s simply an “old school” method of estimating wildlife populations, and we now have additional options that weren’t available some two decades ago.

How does an SPR model generate population estimates?

SPR models produce population estimates using a variety of data. There are “primary” and “auxiliary” data sources.

Primary data sources include:

- age and sex-specific harvest data (e.g., Telecheck data and tooth mail-in program)
- catch-per-unit effort (hunter effort data, from elk permit sales and elk hunter survey data)
- data derived from the bull and cow elk mortality projects (University of Kentucky, 2011-2015; used to reconstruct populations and to help estimate numbers of at-risk animals/ harvest probabilities).
- GPS elk collars deployed by KDFWR elk program staff.

Auxiliary data sources include:

- natural, or non-harvest, mortality sources (bull and cow mortality research projects, ancillary data derived from KDFWR-deployed GPS and VHF collars on elk).

What are key considerations to keep in mind when reading this report?

- SPR models require, *at minimum*, 3-5 years of sequential data to produce estimates with lower variance and narrower confidence intervals
    - This initial SPR model incorporates the bare minimum amount of data required to inform an SPR model.
        - This results in lower precision, limits the ability to assess the impact of additional auxiliary data, and also limits the amount of flexibility to use various model-fitting techniques.
    - Elk are the only species that KDFWR manages whose population models produce confidence intervals (other species' population models only yield point-estimates and trends).
    - KDFWR is currently only working with 3 years of sequential data for the female component of this model, and some of that was combined from various sources (e.g., cow research project, tooth data, etc.) to inform the model.
- Population estimates generated using elk collar data within a given year (e.g., bull or cow elk abundance) are influenced by the number of collars deployed and collared animals' geographic distribution.
    - When those collared animals are centralized in specific areas, those data are used to represent the entire elk zone, which decreases model stability (i.e., having the bulk of collar data in higher hunter-density areas may bias abundance and survival estimates low due to increased harvest pressure).

What must KDFWR accomplish to improve this model over the next 3-5 years?

To improve the functionality and applicability of the Kentucky Elk SPR Model, the Elk Program staff recommends implementing the following (per the recommendations of the model developers):

- Require the tooth mail-in program to become mandatory for all hunters. An accurate representation of the age-at-harvest for males and females has proven to be a critical component of the SPR modelling techniques, and provides insights into the overall age structure and composition of the herd
    - This would require little investment from KDFWR staff and hunters but would provide vital data
    - Non-compliant hunters would be ineligible to apply for any Kentucky quota hunts for the following year
- Catch-per-unit effort, or hunter effort, is a necessary component of the SPR model. As such, the mandatory postseason elk hunter survey requirement, as recommended by the Commission and approved by the legislature will ensure collection of these data yearly.
- Increase the number and distribution of GPS collars on the landscape to provide ample time-series data to support enhancement of the model over time
    - Obtain data transmitted from ~100 collared elk (approximately 50 per sex) across the landscape per year
    - Use aerial captures for cost effectiveness and to minimize risks to captured elk.
    - Data derived from the collars will also support other uses (e.g., movement and habitat use/selection analyses)

What are future research needs?

Calves and yearling cows: There is little mention of these components in the SPR Report, other than to say that there is scant information regarding calf and yearling survival estimates, both of which would provide important primary and auxiliary data sources for the SPR Model. Calf and yearling survival estimates are often quite difficult to ascertain in typical population monitoring, although both have important implications for a population's growth given that each may be a limiting factor in said growth, and there can be high variability in survival both temporally and spatially.

- Calf survival:
  - No research has been conducted on survival and habitat use characteristics on elk calves since Bowling et al. 2009 (study 2004-2008)
    - Many of the elk captured during this project were captured opportunistically only on mine lands, and many of the calves captured were more than 7 days old
  - Habitat use data suggest an increase in elk use of forested habitats coupled with a decreased use of available habitat on surface mines
    - In a pilot vaginal implant transmitters (VITs) study during the cow elk mortality project (2013-2014), we observed some elk calves being born in forested areas
  - The high number of elk that could be captured via helicopter crew provides a unique opportunity to produce an unbiased sample of elk calves through the use of VIT coupled with a neolink adult GPS collar

- Yearling survival and reproduction:
  - Because we have traditionally been limited to predominantly opportunistic capture methods, we have never before had a large enough sample size to statistically quantify demographic rates of yearling females, namely survival and reproductive potential.
    - Although we cannot say for certain that we can specifically target yearling females, the *potential* for a viable sample of yearling females through aerial captures provides a unique opportunity to assess this critical component of an elk population
      - In 2018, 14 yearling females were captured by a helicopter crew as opposed to just one with a corral trap and one with darting
    - Blood samples should be collected to determine pregnancy rates, VITs can be inserted to determine the rate at which yearlings' calves are recruited (upon successful observation of a fetus with an ultrasound), and yearlings can be captured in subsequent years (or observed), through free-range darting or subsequent aerial captures, to determine pregnancy in the following year.

What are other key needs and considerations going forward?

In addition to the immediate benefits that the SPR Model will provide, there are potential longer-term benefits as well. If KDFWR can continue to enhance this model with additional data and take the necessary steps to refine it in the short term (within 3-5 years), there is potential to improve its functionality and even surpass original expectations. Collecting the necessary information that allows for a complete and rigorous dataset could give us the ability to monitor the eastern Kentucky elk population at more finite levels, like within each management unit or county.

Likewise, many of the demographic parameters collected in this undertaking, such as survival and pregnancy rates for each sex and age class, can also be used in our life-table model (historic population model). As the SPR model parameters become more precise, the cross-referencing of those variables in both models will provide even more robust population estimates through the use of competing (or complementary) models.

There is great potential in the coming years to examine and refine these important population models for understanding and managing the eastern Kentucky elk herd. However, this undertaking will require a significant investment in staff time and other resources. The Elk Program is currently understaffed and these additional efforts will be extremely difficult under current workload expectations. As such, it would be desirable to enlist the help of two graduate students and supporting technicians to handle the many components of the additional, required work. If KDFWR is to continue to use the SPR Model to help guide our management efforts, we should maximize its effectiveness for future use and take advantage of all the opportunities available. KDFWR must ensure it is managing the elk herd in a way that supports the department’s mission of conserving wildlife resources and providing recreational opportunities to Kentucky’s hunters and wildlife watchers.

Kentucky Elk Statistical Population Reconstruction Modeling Project

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Final Report

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Overview

The Kentucky Department of Fish and Wildlife Resources requested we develop a Statistical Population Reconstruction (SPR) model for their elk population. Using available data, we developed the model and assessed abundance, harvest probabilities, and natural survival. We outline model development, data used, recommendations, and results. The appendix provides a full accounting of model assumptions and implications of violating those assumptions. Computer code we used to run the model is included. The model begins in 2011, following permit differentiation for rifle and archery hunters. There are 3 age-classes in the model, calf, yearling and adult. The adult age-class encompasses all ages older than a yearling. There are 3 periods in which antlered males (yearling and adult age-classes) are harvested, Bull Archery, Bull Rifle and Either-Sex Archery. There are two periods when antlerless males (calves) and females (all age-classes) can be harvested, Either-Sex Archery and Cow Rifle.

The Data

Age-at-harvest

The age-at-harvest data 2011 through 2013 are exclusively from radio-collared animals. In 2014 age-at-harvest data comes from a combination of collared animals and tooth aging data. Age-at-harvest data from 2015 through 2016 come exclusively from tooth aging data. The female portion of the model begins in 2014 due to the small sample size of age-at-harvest data for females prior to 2014. The number of male calves harvested is enumerated via mandatory checking and the number of female calves harvested is assumed to be equal to the number of male calves harvested. This assumption is made because the number of female calves harvested is not enumerated and calves are assumed to be born at an equal sex ratio and are assumed to be unaffected by sex-based hunter selectivity. Age-at-harvest data were aggregated across all periods of harvest (Table 1 and Table 2). The age-at-harvest data were used to estimate the proportion of the harvest which comes each non-calf age-class. The annual age-specific harvest proportions calculated from the age-at-harvest data were then applied to the total non-calf harvest from each harvest period in order to generate expected harvest counts for each age-class and harvest period annually (Table 3 and Table 4). This assumes the age-distribution of the harvest is the same for both rifle and archery hunters. The use of expected harvest counts rather than actual harvest counts (with an aging proportion) likely leads to an under-estimation of the variance of the resulting parameter estimates. Male models with only 3 age-classes were unstable, so the number of age-classes was expanded for both males and females to, calf, yearling, 2-years-old and 3+ years-old.

In actuality there are more than only 4 harvest periods, the Either-Sex Archery season occurs in two (2011-2014) and in some years three (2015-2016) non-consecutive periods. In 2015 and 2016 Cow Rifle harvest happens in two non-consecutive week long periods separated by a week of Either-Sex Archery. Given that the late archery periods do not have more than 30 animals harvested in either-sex, we were unable to probabilistically model the late either-sex archery periods as separate periods. We then had two options, to treat these harvest periods as known removals and simply subtract the number of animals harvested form the totals, or assume that all of the Either-sex Archery harvest happens in the first Either-sex Archery period. We decided that the misspecification of the order of such low harvest counts would have a minimal effect on the modeling process and opted to assume that all of the Either-Sex Archery harvest happens in the first Either-Sex Archery period.

Table 1. Male age-at-harvest data for Kentucky elk across all harvest periods combined.

Year	Calf	Yearling	2	3+
2011	11	0	1	14
2012	11	1	1	41
2013	9	0	2	23
2014	11	0	4	37
2015	7	1	14	64
2016	13	3	15	77

Table 2. Female age-at-harvest data for Kentucky elk across all harvest periods combined. Female calf harvest is assumed equal to male calf harvest.

Year	Calf	Yearling	2	3+
2011	11	0	0	7
2012	11	0	0	5
2013	9	0	4	9
2014	11	5	8	28
2015	7	13	26	52
2016	13	12	21	43

Hunter effort

Hunter effort data were enumerated as the number of permits purchased for each harvest period each year (Table 3 and 4). Harvest and effort were pooled for bow and crossbow archery harvest, assuming there is no difference in harvest efficiency between the two methods of harvest. Given the limited opportunity in a hunter's life time to purchase a tag it is reasonable to assume fairly consistent effort on average between tag holders once they are purchased. However, continuing to survey hunters about the number of days or hours spent hunting will allow us to assess this assumption and may increase the variability in hunter effort metric and thus allow a more precise estimation of the catch-effort relationship.

Table 3. Male total elk harvest and number of permits purchased by period. Male harvest during Cow Rifle harvest is exclusively calves.

	Bull Archery		Bull Firearm		Either Sex Archery		Cow Rifle	
Year	Number of Permits Purchased	Total Male Harvest	Number of Permits Purchased	Total Male Harvest	Number of Permits Purchased	Total Male Harvest	Number of Permits Purchased	Total Male Harvest*
2011	79	50	118	136	298	22	328	11
2012	88	58	135	148	322	28	360	10
2013	93	43	147	160	328	38	405	4
2014	93	45	145	146	321	44	400	7
2015	94	38	143	159	285	46	346	5
2016	98	38	139	146	296	58	323	9

Table 4. Female total elk harvest and number of permits purchased by period.

Year	Either-Sex Archery		Cow Rifle	
	Number of Permits Purchased	Total Female Harvest	Number of Permits Purchased	Total Female Harvest
2014	321	55	400	183
2015	285	43	346	229
2016	296	42	323	208

Auxiliary

Auxiliary data come from collared animals which were primarily collared on limited entry areas near release sites. We used the raw database with tagging dates, mortality dates and source of mortality to determine, for each year of the reconstruction and sex, the number of animals at risk at the start of the harvest season, the number of animals harvested, the number of animals which died during the year not due to harvest and the number of animals which survived the year. Given the high harvest rates exhibited by these tagged animals it was determined that we should not use the harvest rate information available in these data. However, without some harvest rate or abundance information we were unable to get the model to converge to reasonable estimates, we consequently included only the final year of harvest auxiliary information for adult age classes in the model when the harvest rates were the lowest. The non-harvest mortality rates from the auxiliary data were used in all years of the reconstruction for both sexes. These data were available 2011-2015 for males and 2013-2015 for females. Female auxiliary data from 2013 and 2014 were combined into 2014, because the female model did not start until 2014 and survival was assumed to be constant across years. The female harvest auxiliary sample size was doubled in the final year in order to weight the auxiliary likelihood higher and further reduce the estimated harvest rate in the model. Reported variance estimates are based on the true auxiliary sample size.

Table 5. Male auxiliary data from radio-collared animals for a Kentucky elk population 2011-2015. Natural mortality information was included in the model for all years. Harvest mortality information was only included in the model in 2015.

Season Year	At Risk	Harvested	Died	Survived
2011	57	8	5	44
2012	104	42	12	50
2013	96	23	16	57
2014	75	17	6	52
2015*	52	3	1	48
Total	384	93	40	251

Table 6. Female auxiliary data from collared animals for a Kentucky elk population 2013-2015. Natural mortality information was included in the model for all years. Harvest mortality information was only included in the model in 2015.

Season Year	At Risk	Harvested	Died	Survived
2013	37	8	2	27
2014	78	20	3	55
2015	52	2	1	49
Total	167	30	6	131

The Model

SPR models are primarily defined by the configuration of their age and sex specific demographic parameterizations (Table 7). In the final model selected to reconstruct Kentucky's elk population all calves have a single harvest vulnerability coefficient shared across both sexes and all periods of harvest. Given our assumption of equal calf harvest between males and females the male and female calves were assumed to have equal harvest vulnerability in the model. Yearling males have a single harvest vulnerability shared across both rifle and archery harvest. Yearling females have a single harvest vulnerability shared across both rifle and archery harvest. In each case (calves, yearling males and yearling females) harvest was very low making it impossible to differentiate between the very low harvest vulnerability coefficient for archery harvest and the very low harvest vulnerability coefficient for rifle harvest. Adult males (age class 2 and 3+) have separate harvest vulnerability coefficients for the Bull Archery, Bull Rifle and Either-Sex Archery harvest periods. Adult females (age class 2 and 3+) have separate harvest vulnerability coefficients for the Either-Sex Archery and Cow Rifle harvest periods. A single natural survival rate is estimated for each sex which is assumed to be constant across years.

Table 7. An illustration of the harvest vulnerability coefficient configuration for the final SPR model used to reconstruct a Kentucky elk population 2011-2016.

<table>
<tr><th>Age-Class</th><th>Sex</th><th>Bull Archery</th><th>Bull Rifle</th><th>Either-Sex Archery</th><th>Cow Rifle</th></tr>
<tr><td>Calf</td><td>both</td><td>N/A</td><td>N/A</td><td colspan="2">1</td></tr>
<tr><td>yearling</td><td>male</td><td colspan="3">1</td><td>N/A</td></tr>
<tr><td>adult</td><td>male</td><td>1</td><td>2</td><td>3</td><td>N/A</td></tr>
<tr><td>yearling</td><td>female</td><td>N/A</td><td>N/A</td><td colspan="2">1</td></tr>
<tr><td>adult</td><td>female</td><td>N/A</td><td>N/A</td><td>1</td><td>2</td></tr>
</table>

Random effects

We attempted to estimate correlated random effects for each harvest vulnerability coefficient described above. However, initial model runs indicated that random effects were inestimable for calves and male yearlings in any period and for female yearlings and adults in the Either-Sex Archery period of the harvest season. Therefore, random effects were only included for adult males in the Bull Archery, Bull Rifle and Either-Sex Archery harvest periods, for yearling females in the Cow Rifle period, and for adult females in the Cow Rifle period (Table 8).

Table 8. An illustration of the random effects configuration for the final SPR model used to reconstruct a Kentucky elk population 2011-2016. Blank cells indicate no random effects.

Age-Class	Sex	Bull Archery	Bull Rifle	Either-Sex Archery	Cow Rifle
Calf	both	N/A	N/A		
yearling	male				N/A
adult	male	1	2	3	N/A
yearling	female	N/A	N/A		1
adult	female	N/A	N/A		1

Results

Based on the best model described above total elk abundance prior to the Bull Archery season in the region of Kentucky being modeled was 12,188 (SE=5,226.3) in 2014 and declined to 10,577 (SE=4,533.5) in 2015 rising to 13,157 (SE=5,350.1) in 2016 (Table 9 and Figure 3). Total abundance was only estimable for years in which female abundance was estimated. Female abundance estimation began in 2014. Total male abundance ranged from a high of 11,762 in 2012 to a low of 5,788 in 2015 (Table 9 and Figure 3). The largest decline in male abundance was from the 3+ age-class which had a high abundance estimate of 9,605, in 2012 and a low abundance estimate of 3,607 in 2015 (Table 10). All other male age-class abundance estimates did not show a discernable trend (Figure 1). Total female abundance showed a slight increasing trend with an abundance estimate of 4,936 in 2014 and an abundance estimate of 5812 in 2016 (Table 9 and Figure 3). There were no discernable trends in abundance estimates for any female age-class over the 3 years females were modeled (2014-2015) (Figure 2).

Table 9. Sex-specific and total annual abundance estimates 95% confidence interval (CI) bounds for an elk population in Kentucky 2011-2016.

	Year	Male Abundance	Standard Error	CV of Male Abundance	Upper 95% CI bound	Lower 95% CI bound
Total Abundance	2011	11729.0	4635.4	0.395	20814.3	2643.7
	2012	11762.0	4925.0	0.419	21414.9	2109.1
	2013	8550.7	3542.1	0.414	15493.3	1608.1
	2014	7251.4	2979.7	0.411	13091.7	1411.1
	2015	5788.8	2390.1	0.413	10473.3	1104.3
	2016	7344.7	3152.3	0.429	13523.1	1166.3
	Year	Female Abundance	Standard Error	CV of Female Abundance	Upper 95% CI bound	Lower 95% CI bound
	2014	4936.2	3191.9	0.647	11192.4	0.0
	2015	4788.4	2998.1	0.626	10664.7	0.0
	2016	5812.1	2695.2	0.464	11094.6	529.6
	Year	Total Abundance	Standard Error	CV of Total Abundance	Upper 95% CI bound	Lower 95% CI bound
	2014	12188.0	5226.3	0.429	22431.5	1944.5
	2015	10577.0	4533.5	0.429	19462.6	1691.4
	2016	13157.0	5350.1	0.407	23643.2	2670.8

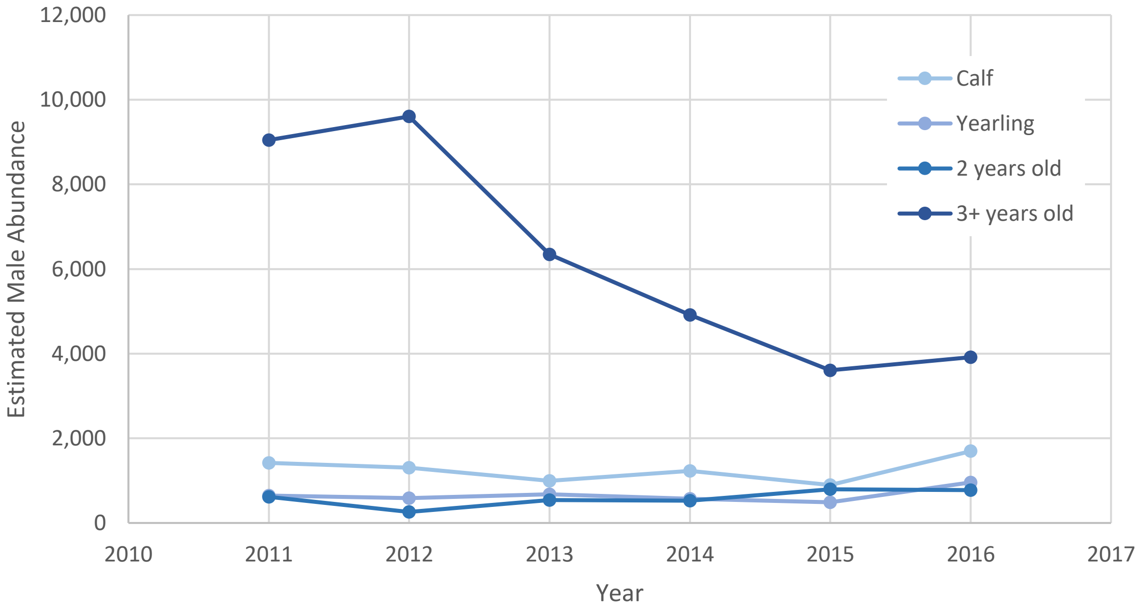

Figure 1. Age-specific abundance estimates for male elk in Kentucky 2011-2016. Declines in abundance of age-class 3+ correspond with declines in catch-per-unit-effort for age-class 3+ in bull archery and bull rifle harvest.

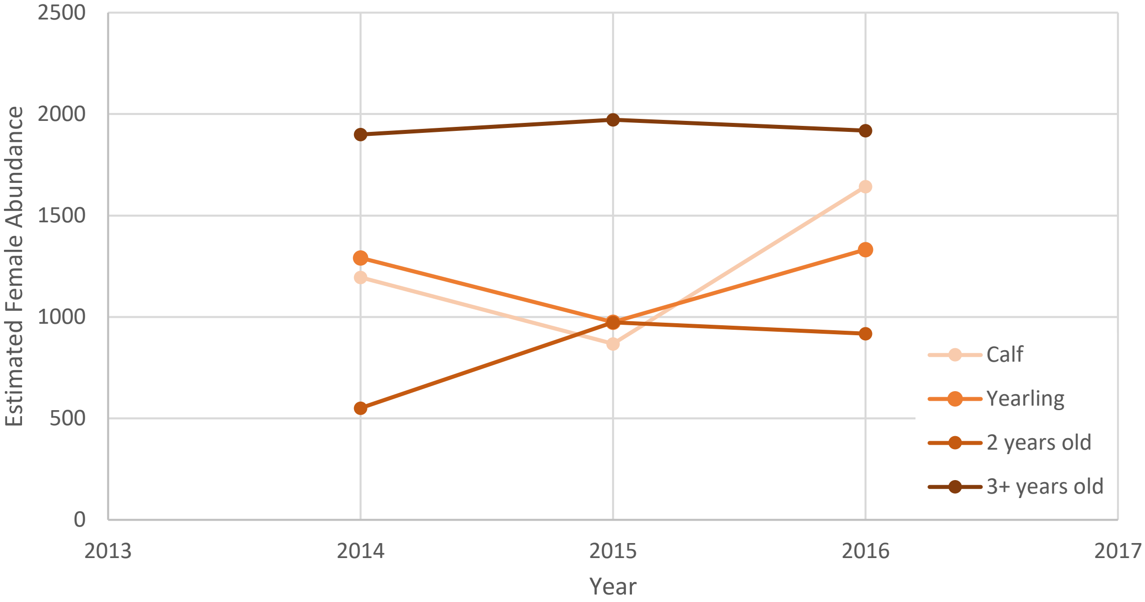

Figure 2. Age-specific abundance estimates for female elk in Kentucky 2014-2016.

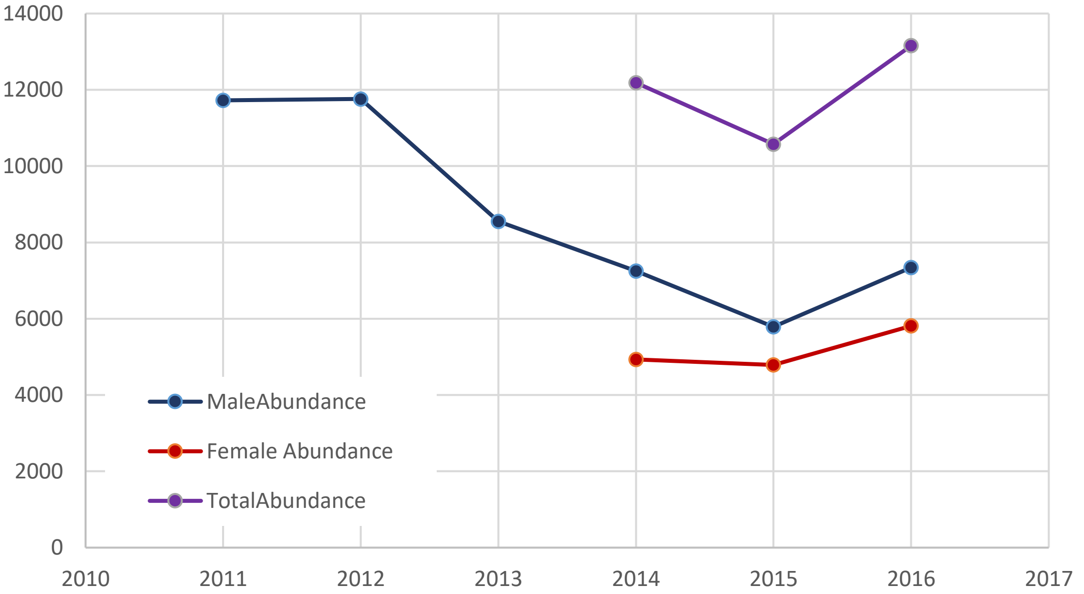

Figure 3. Sex-specific and total annual abundance estimates for an elk population in Kentucky 2011-2016.

Harvest probability was estimated for each age-class and harvest period individually and combined across all periods for each sex (Table 12). The highest age and period specific harvest probability estimate for males was 2+ year old males during the Bull Rifle season which ranged between 1.37% in 2011 and 3.52% in 2015. The highest age and period specific harvest probability estimate for females was 2+ year old females during the Cow Rifle season which ranged between 7.17% in 2014 and 6.13% in 2015. Natural survival was estimated to be 0.845 (SE= 0.0210) for males and 0.958 (SE=0.0194) for females. Natural survival encompasses all sources of mortality outside of legal reported harvest and was assumed constant across age-classes and years. The lower than expected total annual survival, the probability of living through an entire year from any source of mortality, was also estimated for each age and sex-class (Table 11).

Table 10. Age-specific abundance estimates for male (2011-2016) and female (2014-2016) elk in Kentucky.

	Male				
	Year	Calf	Yearling	2 years old	3+ years old
Age-Specific Abundance	2011	1,419.4	645.3	618.9	9,045.5
	2012	1,307.7	588.0	260.8	9,605.1
	2013	993.1	674.9	538.7	6,344.1
	2014	1,234.0	571.4	530.2	4,915.9
	2015	896.6	489.0	795.5	3,607.7
	2016	1,695.9	958.0	775.0	3,915.8
	Female				
	Year	Calf	Yearling	2 years old	3+ years old
	2014	1194.5	1291.3	551.1	1899.4
	2015	868.0	974.7	973.5	1972.2
	2016	1642.8	1332.2	918.7	1918.4

Table 11. Total annual survival estimates for by sex and age class for an elk population in Kentucky 2011-2016.

Total Survival Estimates							
Male				Female			
Year	Calf	Yearling	2+ years old	Year	Calf	Yearling	2+ years old
2011	0.838	0.838	0.827	2011			
2012	0.834	0.835	0.822	2012			
2013	0.837	0.837	0.816	2013			
2014	0.837	0.837	0.809	2014	0.949	0.936	0.875
2015	0.838	0.838	0.798	2015	0.950	0.919	0.881
2016	0.838	0.837	0.803	2016	0.950	0.929	0.886

Table 12. Period specific and total annual harvest probability estimates for male and female elk in Kentucky 2011-2016.

Harvest Probability Estimates

Male

Bull Archery

Year	Calf	Yearling	2+ years old
2011	0	0.0013	0.0050
2012	0	0.0014	0.0055
2013	0	0.0015	0.0067
2014	0	0.0015	0.0074
2015	0	0.0015	0.0084
2016	0	0.0016	0.0084

Bull Rifle

Year	Calf	Yearling	2+ years old
2011	0	0.0019	0.0137
2012	0	0.0022	0.0152
2013	0	0.0024	0.0223
2014	0	0.0023	0.0273
2015	0	0.0023	0.0352
2016	0	0.0022	0.0315

Either-Sex Archery

Year	Calf	Yearling	2+ years old
2011	0.0038	0.0047	0.003
2012	0.0041	0.0051	0.003
2013	0.0042	0.0052	0.005
2014	0.0041	0.0050	0.008
2015	0.0036	0.0045	0.012
2016	0.0038	0.0047	0.010

Cow Rifle

Year	Calf	Yearling	2+ years old
2011	0.004	0	0
2012	0.005	0	0
2013	0.005	0	0
2014	0.005	0	0
2015	0.004	0	0
2016	0.004	0	0

Total Annual

Year	Calf	Yearling	2+ years old
2011	0.0077	0.0077	0.0210
2012	0.0084	0.0085	0.0230
2013	0.0091	0.0089	0.0334
2014	0.0089	0.0088	0.0415
2015	0.0078	0.0082	0.0541
2016	0.0077	0.0084	0.0490

Female

Either-Sex Archery

Year	Calf	Yearling	2+ years old
2014	0.0041	0.0063	0.0156
2015	0.0037	0.0056	0.0139
2016	0.0038	0.0058	0.0144

Cow Rifle

Year	Calf	Yearling	2+ years old
2014	0.0052	0.0165	0.0717
2015	0.0045	0.0351	0.0670
2016	0.0042	0.0247	0.0613

Total Annual

Year	Calf	Yearling	2+ years old
2014	0.0092	0.0225	0.0853
2015	0.0081	0.0400	0.0791
2016	0.0079	0.0300	0.0740

Most of the data which could be considered indices to abundance that we have available stop in 2014, however catch-per-unit-effort (CPUE) was calculable for each harvest period and age-class. The Bull Rifle CPUE stays relatively flat through time, male Either-Sex Archery CPUE has steadily increased through time, and the Bull Archery CPUE tracks the total male abundance estimates from the model declining

2011-2013 and then leveling off (Figure 4). Age-specific CPUE for adult males shows a decline in the number of age-class 3+ males harvested for each permit sold for the Bull archery and Bull Rifle portions of the harvest season (Figure 5). The decline in CPUE for older males is a strong indicator that there may be a decline in age-class 3+ male abundance, as was estimated in the SPR model. An alternative explanation for the change in CPUE is that age-class 3+ males are getting more difficult to harvest. Given some issues such as the changing landscape caused by declining mining activity, we cannot rule out that the changes we are seeing are not a function of both some decline in abundance of older animals and some changes in harvest vulnerability. However, a decline in abundance for age-class 3+ is the most likely driver of the changes we are seeing, given the increases in CPUE seen in the age-class 2 over the same time period. Neither of the female CPUE effort metrics track the female abundance estimates, however there are only three years of data available, making a corollary comparison difficult at this time.

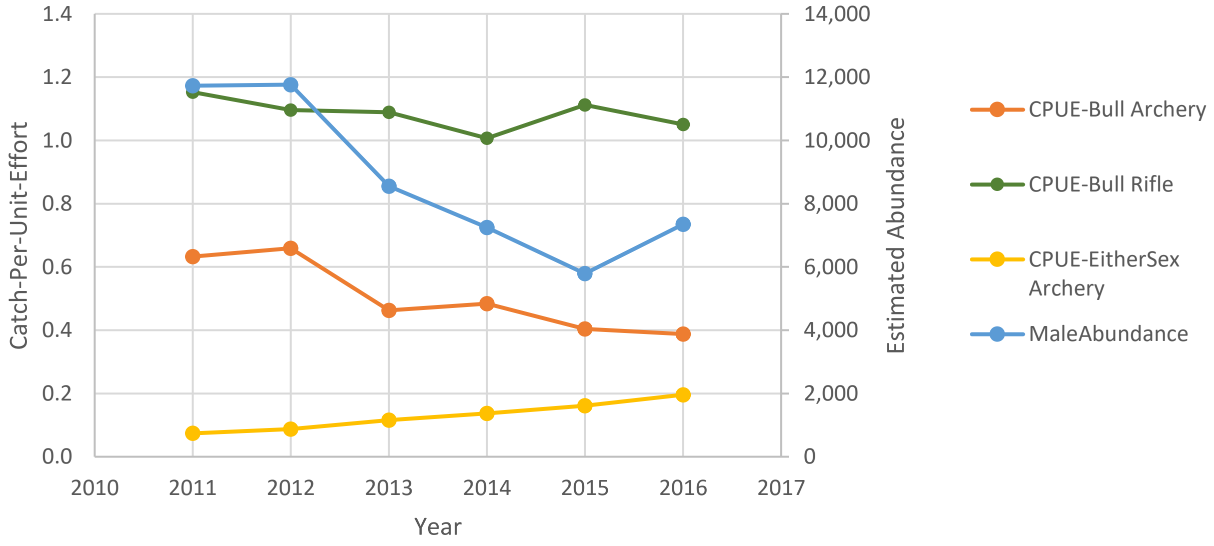

Figure 4. Catch-Per-Unit-Effort (CPUE) and estimated male abundance for a Kentucky elk population 2011-2016.

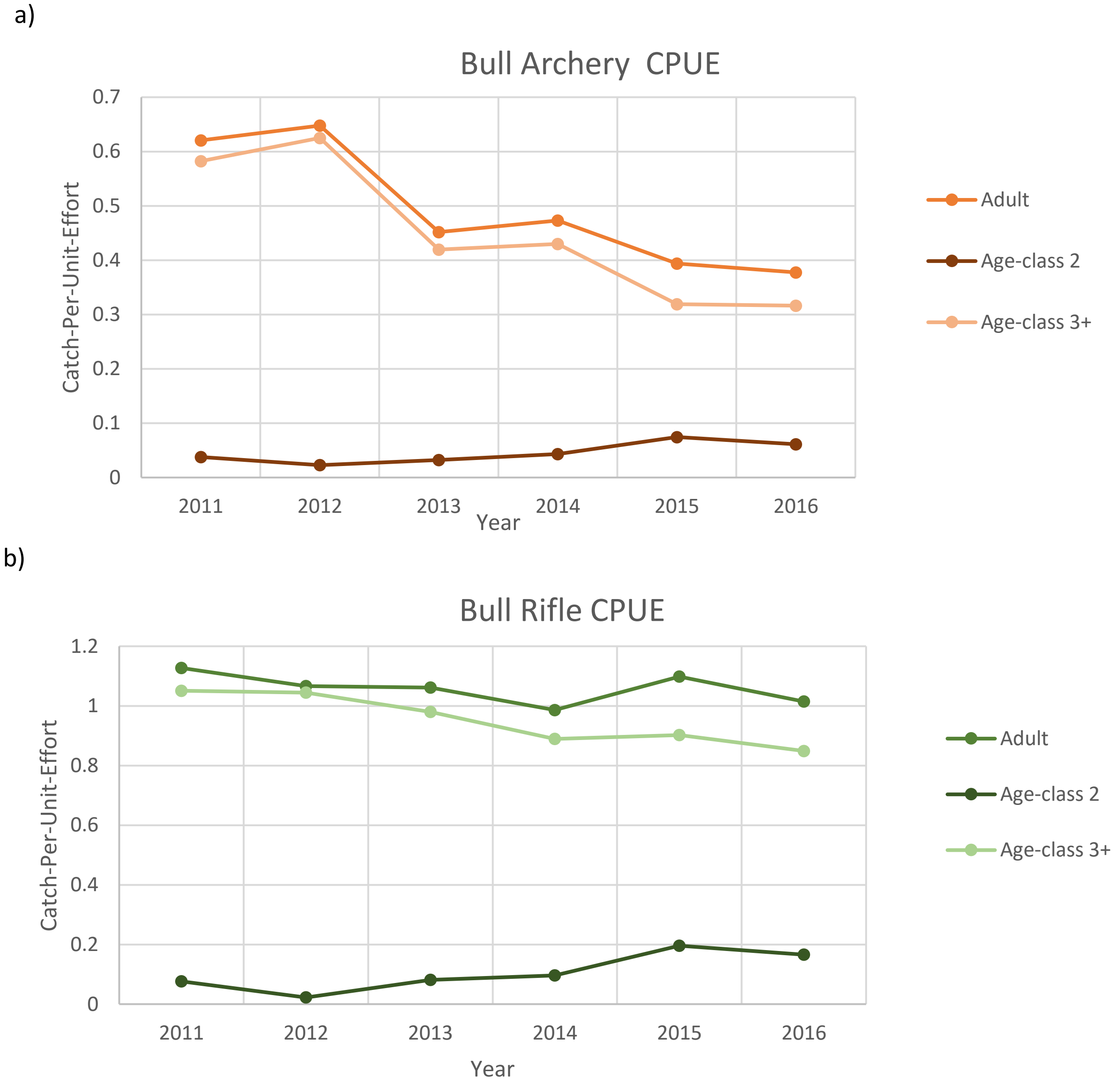

Figure 5. Adult male age-class specific Catch-Per-Unit-Effort (CPUE) for the bull archery (a) and bull rifle (b) portions of the harvest season. Declines in CPUE for age-class 3+ males correspond with estimated declines in

Table 13. Sex-specific and total annual abundance estimates with 80% and 90% confidence interval (CI) bounds for an elk population in Kentucky 2011-2016.

	Year	Male Abundance	Standard Error	Upper 90% CI bound	Lower 90% CI bound	Upper 80% CI bound	Lower 80% CI bound
Total Abundance	2011	11729.0	4635.4	19331.0	4127.0	17662.3	5795.7
	2012	11762.0	4925.0	19838.9	3685.1	18065.9	5458.1
	2013	8550.7	3542.1	14359.8	2741.6	13084.6	4016.8
	2014	7251.4	2979.7	12138.2	2364.6	11065.5	3437.3
	2015	5788.8	2390.1	9708.5	1869.1	8848.1	2729.5
	2016	7344.7	3152.3	12514.4	2175.0	11379.6	3309.8
	Year	Female Abundance	Standard Error	Upper 90% CI bound	Lower 90% CI bound	Upper 80% CI bound	Lower 80% CI bound
	2014	4936.2	3191.9	10171.0	0.0	9021.9	850.5
	2015	4788.4	2998.1	9705.3	0.0	8626.0	950.8
	2016	5812.1	2695.2	10232.2	1392.0	9261.9	2362.3
	Year	Total Abundance	Standard Error	Upper 90% CI bound	Lower 90% CI bound	Upper 80% CI bound	Lower 80% CI bound
	2014	12188.0	5226.3	20759.1	3616.9	18877.6	5498.4
	2015	10577.0	4533.5	18011.9	3142.1	16379.8	4774.2
	2016	13157.0	5350.1	21931.1	4382.9	20005.1	6308.9

Recommendations

Based on our work, we offer the following recommendations:

1. The state of Kentucky is currently collecting age-at-harvest data through voluntary tooth submission and hunter effort data through post season survey which will increase the stability and precision of the SPR models presented here. We recommend continuing to collect these age-at-harvest and hunter effort data sources. Increasing precision and stability of SPR models through the collection of additional harvest data alone is a long term commitment and process.

2. Collecting additional auxiliary information through geographically wide spread collar deployment on both male and female elk would increase model stability and increase precision of the resulting parameter estimates. We recommend maintaining 30-40 collared adult animals (split evenly between males and females) a year, spread across the elk range for the next 5 years in order to collect representative harvest rate information. After 3 years of additional data collection we recommend re-evaluating the auxiliary data collection strategy and precision goals.

We were able to evaluate a range of sample sizes, from 10 to 1000 animals tagged animals, with the number of tags split evenly between adult males and adult females, on the landscape annually for 3 years (Figure 6).

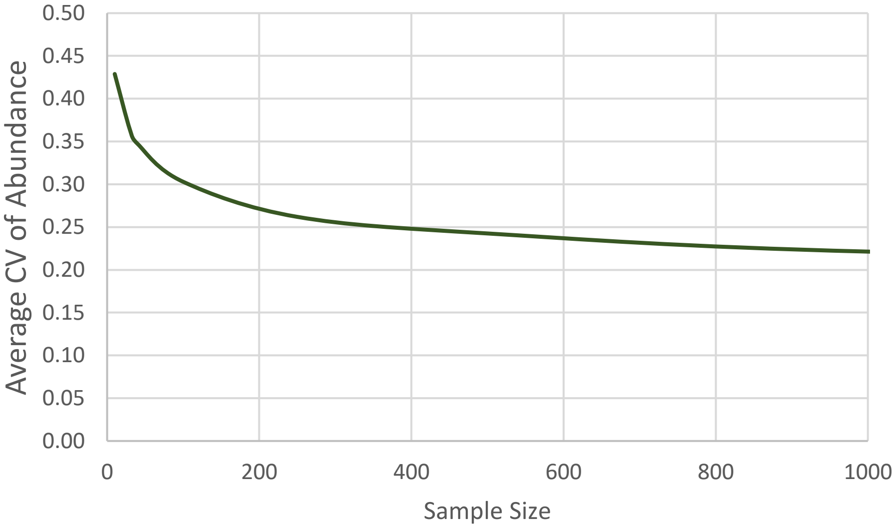

Figure 6. Average CV of total abundance at sample sizes from 10 to 1000 radio-collared adult animals on the landscape annually for 3 years. The sample size is split evenly between males and females.

The limited number of years of harvest and hunter effort data available (6 years for males and 3 years for females) contributes to the low precision we are seeing now and limits our ability to assess the impacts of additional auxiliary information. As such the sample size precision relationship shown in Figure 6 should be viewed as conservative approximations of potential gains in precision. With 5 years of 30-40 collars we expect an improvement in precision by about 10% (i.e., from 40% to 30%). With 5 years of 100 collars we would expect to see additional improvement of precision by about 15%. We see significantly diminishing returns in precision with more than 100 tagged adult animals on the landscape each year.

3. Additionally, the auxiliary information on calf and yearling survival is scarce. Given likely differences in calf, yearling, and adult survival and potential for high inter-annual variability, it would be beneficial to collect additional information on calf and yearling survival should there be interest in estimating natural survival rates specific to these age classes.

4. Finally, increased tooth submission would address a number of the assumptions detailed in Appendix 1. If we can successfully increase tooth submission on a short-term basis it would allow us to evaluate many of the assumptions we are making that involve the tooth submission data. We recommend evaluating ways to increase tooth submission and consideration of mandatory tooth submission.

5. These models and the code provided demonstrate the utility of SPR for modeling the Kentucky elk herd and estimating important status and trend information. One tremendous strength of SPR models is that they are hand-tailored to data collected by an agency and can be updated as new data become available. One potential drawback is that as new auxiliary data are collected, new models need to be developed based on the likelihood theory applied here. Thus, models need to be customized for new auxiliary data and code updated. These updates can result in changes associated with model convergence and numerical optimization which require special attention.

Appendix 1: Model assumptions

An integral phase of the SPR modeling process is deciding how best to model the available data and which assumptions need to be made. For each of the assumptions made during the process of modeling elk in Kentucky we discuss the reason the assumption was made, the implications of violating the assumption and recommendations for how to avoid making the assumption in future modeling efforts. The majority of the assumptions made in this modeling process arise from the relatively low amount of harvest information we currently have available.

1. A minimum of five years of age-at-harvest and hunter effort data are required to construct an SPR model. Age-at-harvest data from hunter submitted teeth were only available for three years (2014-2016). In order to be able to construct an SPR model we used three years of age-at-harvest data from collared males (2011-2013), allowing us to have 6 years of male age-at-harvest data. In doing so we make the assumption that the age-at-harvest information from collared males is representative of the age composition of the male harvest for the entire population from 2011 to 2013. This is a reasonable assumption if we can assume that male elk were tagged at random from the population and that male elk with collars are harvested in the same age-distribution as un-collared males. If this assumption is violated the age-specific estimates of male abundance 2011-2013 may be biased. In order to avoid this assumption in the future we simply need to continue collecting male age-at-harvest data. Eventually we will have enough years of age-at-harvest data that the collar based age-at-harvest data from 2011-2013 can be dropped from the model.

2. Calf harvest of elk in Kentucky is very low, and the number of calf teeth returned for ageing is even lower, so we had limited information on female calf harvest. However, male calf harvest is enumerated in harvest reporting. In order to have a reasonable estimate of the number of female calves harvested we assumed that female calf harvest was equal to male calf harvest. This is a reasonable assumption if we assume that the sex ratio at birth is 1:1, male and female calves have equal survival from birth to the start of the harvest season and there is no sex-based selection in calf harvest. If the number of female calves harvested is mis-specified the resulting female calf abundance estimates are likely to be biased. Given the very few number of male calves harvested, any misspecification of female calf harvest is likely to be minimal and thus have a minimal effect on model output. However, if more accurate estimates of female calf abundance are a high management priority, we could avoid making this assumption if we had teeth from a very high proportion of the harvest via mandatory tooth submission.

3. In order to effectively apply SPR models there need to be a minimum of 30-50 animals harvested and aged for each sex in each period being modeled. Based on that criteria, it would be difficult to model any of the Either-Sex archery periods by themselves, except females in the first Either-Sex archery period, even if we had 100% ageing. In order to construct the SPR model with the available data, we made the choice to combined all of the sections of the Either-Sex archery harvest into a single period and model it as if all of the Either-Sex archery harvest occurs prior to the cow rifle harvest period. We know this assumption is violated, resulting in positive bias in harvest rate estimates for the cow rifle season, in which females and young-of-the-year males are harvested. This positive bias in harvest rate in turn leads to a negative bias in abundance. However, the minimal harvest in the later periods means that the magnitude of the bias induced here is very minimal and has very little impact in light of the

other model uncertainties. The only way to avoid combining the Either-Sex archery periods into a single period would be to increase harvest numbers in the later Either-Sex archery periods and have mandatory tooth submission. However, given the minimal effects of this assumption, we recommend no additional action be taken to avoid this assumption.

4. Additionally, there were not enough males or females aged in each harvest period in order to construct age-at-harvest matrices for each of the 3 harvest periods for males (bull archery, bull rifle, Either-Sex archery) and 2 harvest periods for females (Either-Sex archery and cow rifle). We therefore combined the ageing data for males across the 3 harvest periods and all of the ageing data for females across the two harvest periods to estimate a single age-at-harvest distribution for each sex. We then applied the sex-specific age-at-harvest distributions to the total harvest for each of the appropriate harvest periods to generate expected harvest counts. These expected harvest counts were then used to create the SPR model. This makes the implicit assumption that the same age-distribution is taken during each of the 3 male harvest periods and that the same age-distribution is taken during each of the 2 female harvest periods. If this assumption is violated, it could bias age-specific abundance estimates, likely positively biasing abundance estimates for some age-classes within a year and negatively biasing others. However, the magnitude of the bias would be commensurate with the magnitude of the misspecification. So if the proportions are slightly off minimal bias is likely. If the age-distributions taken during each harvest period is changing in a constant trend through time this could present a systematic bias. We recommend evaluating the assumption of equal age-at-harvest distributions across harvest periods. In order to evaluate this assumption we would need 3 years of teeth data with an increased sample size. The sample size could be increased through incentives or mandatory teeth returns.

5. As described above, there is not enough age-at-harvest information from each harvest period to use the actual age-at-harvest counts for each harvest period paired with an ageing proportion. So the options were to use the expected age-at-harvest counts, or to bootstrap the harvest counts and run thousands of iterations of the model with a range of potential age-specific harvest counts. Given the low precision of the estimated parameters and model instability we did not think it was useful to undertake the bootstrapping method at this time. Using the expected harvest counts means that the reported variance estimates of the parameter estimates are likely lower than the actual variance should be. As we collect additional age-at-harvest and hunter effort data the model will become more stable; this would make the boot strapping method appealing and make accurate estimation the precision of the resulting parameter estimates more feasible. We recommend continuing to collect age-at-harvest and hunter effort information into the future and revisiting the concept of bootstrapping to more accurately estimate variances in 3 to 5 years.

6. The number of permits purchased is the only hunter effort metric currently available over the entire modeling period (2011-2016). In using the number of permits purchased as the hunter effort metric in the SPR models we make the implicit assumption that all hunters who purchased a permit expended equal effort. Given the very low likelihood of being drawn for an elk permit, this may be a reasonable assumption. Even if this assumption is mostly correct, collecting more detailed forms of effort can be useful. The number of permits purchased has lower inter-annual variation than would the number of days or hours spent in the field. A higher variation in the effort metric may allow for a more precise estimate of the catch-effort relationship and thus may increase overall precision of parameter

estimates. We recommend continuing to survey hunters annually about the number of hours or days spent in the field hunting to provide a more detailed effort metric for future modeling efforts.

7. The limited number of years of harvest data which were available constrained the potential models which could be fit. This constraint led us to assume that natural survival was constant among years and across age-classes. The resulting estimate of natural survival rate is an average across age-classes and years, which would obscure any potential variation in annual or age-specific survival. As we collect additional age-at-harvest and hunter effort data the model will become more stable and allow for additional natural survival rate parameterizations. Additionally, the auxiliary information on calf and yearling survival is scarce. Given likely differences in calf, yearling, and adult survival and potential for high inter-annual variability, it would be beneficial to collect additional information on calf and yearling survival should there be interest in estimating natural survival rates across these age classes.

Finally, we had to increase the weight of the female harvest probability auxiliary data which came from the collared animals in 2015 in order to stabilize the model. Reweighting the female harvest auxiliary reduced the overall estimated female harvest rate estimates. If the true harvest rates are higher than those estimated in the final model then the reweighting would have introduced positive bias into the female abundance estimates. Regardless of any potential bias introduced, we are concerned that our female abundance estimates are highly dependent on a single year of auxiliary data. In fact, the entire reconstruction currently relies heavily on the 2015 auxiliary data. Given our concerns about the representativeness of the collar data as it relates to the overall population even the low harvest rate estimates in 2015 may be too high, in which case the reported abundance estimates are negatively biased. The collection of additional years of harvest data will help stabilize the model and reduce the dependence of the model on this single year of auxiliary information. We also recommend collecting additional auxiliary information on female harvest rates to more quickly increase model stability and precision.