Modeling Deer Population Control System Dynamics

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December 6, 2020

Abstract— **Hunting is the primary method for deer population management in West Virginia. West Virginia Department of Natural Resources (WVDNR) evaluates and sets harvest management goals on a yearly basis. In this paper we aim to develop and analyze a system of time-dependant ordinary differential models in-order to better understand the dynamics of the white-tailed deer population in West Virginia and the difference in effectiveness of any combination of harvesting methods that ultimately minimize the negative economic consequences caused by overpopulation for all six districts in West Virginia and maintain a healthy equilibrium for the future white-tailed deer population.**

1 Introduction

The booming growth in deer populations across the nation can be described as a wildlife success story. However, this was not always the case as historic unregulated hunting and mass slaughter of deer for their hides brought the nationwide deer population down to critically low levels. Unsurprisingly, after proper population protections, such as regulated hunting methods and enforced licensing, were implemented the deer population was able to make a comeback to near historic population highs. Today, large deer populations, that exceed local population management goals, are a common problematic phenomenon. One of the primary reasons that drives deer population growth is their higher reproductive rates relative to those of other large mammals. Marchinton (2006) explains that, "theoretically, two bucks and four does could produce more than 300 deer in six years without any environmental resistance."

Catastrophic populations of deer, and an unrelenting population growth rate, in any concentrated location is an unfavorable and costly situation for both humans and deers because it can cause an increased frequency of dangerous disruption to domestic life as well as extreme devastation to their own habitat. Human-deer interactions are on the rise in urban areas, where deer-vehicle collisions (DVCs) and damage to personal property are common. According to the National Highway Traffic Safety Administration over one million DVCs occur each year that kill hundreds of people, cause thousands of injuries, and result in over one billion in vehicle damage. Deer population management is an ongoing conflict in the United States for many years, so there have been a multitude of population control methods integrated into harvest and habitat management strategies such as hunting, sterilization, predator introduction, and fencing to help solve overpopulation. Non-lethal and habitat management methods such as fencing or use of repellents have proven to be locally successful but ultimately result in redirecting population pressures elsewhere and do not directly address the foundational problem, too many deer. Therefore, In this paper we will focus our work in understanding harvesting methods that directly and significantly affect deer population size and growth rate.

Unfortunately, the main bottleneck in better modeling and understanding white-tailed deer populations is a lack of methods to accurately produce population estimates. Without reliable data, the prescriptive power of any population control model is significantly reduced. We currently resort to indicators such as total yearly harvest number, harvest sex and age ratios, and deer dropping densities to estimate population size. That said, the total white tail deer population in the United States is currently estimated to be approximately 29.5 million, recorded last in 2017, with a low of 28.6 million in 2014 and a high of 33.5 million in 2000. Though there are many successful population management strategies, regulated hunting is the primary method of white-tailed deer population control throughout the country. This is especially the case in West Virginia, where deer can be found everywhere and hunting is regarded as tradition in which 250,000 - 350,000 licenced members participate on a regular basis each year. In West Virginia, the white-tailed deer population is approximately 550,000 - 650,000 where approximately sixty percent reside in northern and central counties, namely districts 1,3, and 6 in the figure below.

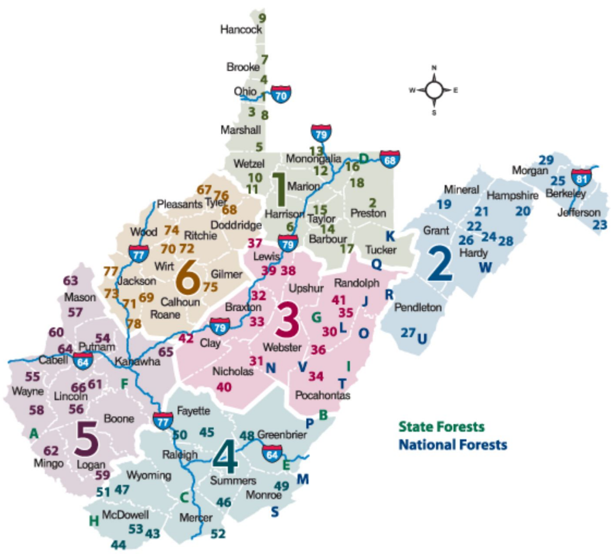

Figure 1: Map of West Virginia broken down by 6 hunting districts

According to State Farm Insurance, an auto insurance company, West Virginia has the highest risk of any state for drivers colliding with deer. In fact, the auto insurance company has also stated that deer collisions make up approximately two thirds of all animal-vehicle collisions. Additionally, WVVA, a West Virginia news channel, has stated that the odds of drivers in West Virginia colliding with a deer is a 1 in 37 chance in October 2020. Given the undeniable potential of overpopulation, there is more incentive now than ever before to fundamentally understand the dynamics of harvesting methods that effectively control the white-tailed deer population size and, as a result minimize, negative economic consequences.

2 Problem Definition

We aim to construct an augmented logistic growth model that incorporates a seasonal harvest of the deer population through a variety of harvesting methods which result in weapon, crop, and indirectly, vehicle collision related deer mortalities. The model will describe the dynamics of the white-tailed deer population given variable interactions between its environment and hunters.

We will initially design a symbolic system dynamic relationship model that maps input parameters to final state values. Next, we will iterate on the symbolic relationship model by including population flow directions and parameter rates and assumptions. After detailing a symbolic representation, we will construct a set of three differential equations that will model the exponential growth pattern of the white-tailed deer population, the harvesting behavior and success of hunters in West Virginia, and the environmental interactions of the white-tailed deer that lead to DVCs. Our goal is to define a set of harvesting guidelines, for each of the 6 districts in West Virginia, that will reduce the total number of DVCs as much as possible while maintaining the white-tailed deer population at an equilibrium or minimum desired population size that significantly dampens population growth.

2.1 Deer Population Data and Assumptions

Our primary source of data is the West Virginia Department of Natural Resources. Their team has done extensive work over the years collecting data for the management of their flora and fauna. The key report that WVDNR publishes every year that pertains to white-tailed deer is the Big Game Bulletin. In 2019, they reported a total of 99,437 white-tailed deer harvested during the hunting seasons. We do not assume, however, that the harvested sex ratios are representative of the population;

rather they demonstrate a propensity for hunters to favor bucks over does and young males.

Sex	Buck Gun	Antlerless	Archery / Crossbow	Muzzleloader	Mountaineer Heritage	Total
Buck	36,472	-	16,606	2,545	337	55,960
Antlerless	-	28,336	12,902	1,977	262	43,477
Total	36,472	28,336	29,508	4,522	599	99,437

Figure 4: Table of harvested populations by type in 2019

Besides regular harvesting seasons, another way deer leave the population is via Wildlife Damage Permits which authorizes landowners to remove deer when their crops are being damaged. This population has recently declined from around 5,500 in 2010 to below 2,000 in 2019 representing <1% of total population and are accounted for in the regular mortality rate. Additionally, State Farm Auto Insurance had around 5,000 deer collision claims in 2019. Actual DVC numbers for 2019 are reported by the Department of Transportation and were not available at the time of this analysis.

Our models assume sufficient vegetation density in West Virginia since 95% of the state's 24,000 square miles is identified as white-tailed deer habitat, and we do not expect that food availability is impactful. The running populations estimates for the last 40 years are a function of hunting data and survey data taken in by the WVDNR each year. The hunting data assumes that the proportion of bucks harvested each season is approximately 10% of the total deer pre-season population. For 2020, this means that the hunting season began with between 550,000 and 600,000 white-tailed deer in population. The survey data works to confirm the hunting data. That is, they assume a certain population density based on the hunting data, and the occasional spotlight surveys report numbers that support that population density assumption.

West Virginia offers multiple regulated deer hunting seasons throughout the year to more than 350,000 hunters. The date breakdown of the yearly hunting season throughout West Virginia is provided in the Figure below.

Season	Sex Hunted	Dates
Buck Gun	Buck	Nov. 23-Dec. 6
Archery and Crossbow	Buck and Doe	Sept. 26-Dec. 31
Antlerless	Doe	Oct. 22-25
Antlerless	Doe	Nov. 23-6
Antlerless	Doe	Dec. 10-13 and Dec. 28-31
MuzzleLoader	Buck and Doe	Dec. 14-20

Figure 5: Table of hunting seasons - West Virginia

3 Modeling

We propose a time-dependant dynamic system of augmented logistic growth models consisting of two ordinary differential equations (ODEs) that represent the change in buck and doe populations over time by incorporating seasonal hunter-prey interactions, yearly driver vehicle collisions, and random seasonal dependent deer roaming behavior.

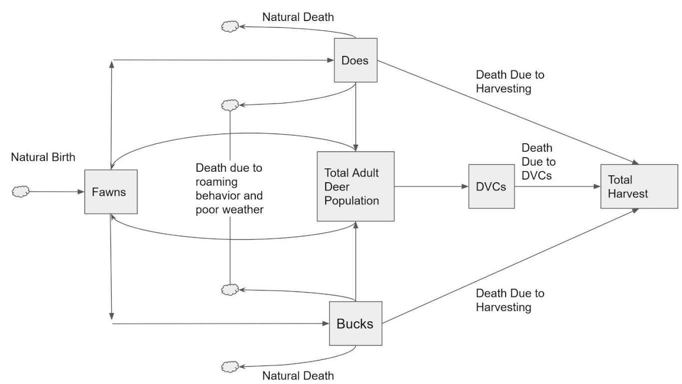

Figure 2: Conceptual model diagram of West Virginia deer population lifecycle. The arrows represent factors affecting the male and female deer population individually and as a whole

The following are the variables and constants we introduced in both of our models:

Parameter	Description
P	Total deer population
P_f	Total doe (female) deer population
P_m	Total buck (male) deer population
K	Deer population carying capacity
C	Deer Vehicle collisions
t	Time in days
d	Natural deer death rate
m	West Virginia district level hunting quota
hbr	Ratio of hunting mortalites that were bucks
hdr	Ratio of hunting mortalites that were does
rf	Scalar factor representing deer roaming behavior
pr	West Virginia district level ratio of total deer population
bsr	Buck enviromental survival rate
dsr	Doe enviromental survival rate

Figure 3: Table of model input parameters

Using the information above we construct the following system of ODE's:

(1)

$$dP_m = r_{max} * bsr * ((P * (1 - (\frac{P}{pr*K})))) - H_{buck_n} - (pr * (\frac{P_m}{P}) * rf * c$$

(2)

$$dP_f = r_{max} * dsr * ((P \ * (1 - (\frac{P}{pr*K})))) - H_{doe_n} - (pr * (\frac{P_f}{P}) * rf * c$$

(3)

$$dP \ = \ dP_m \ + \ dP_f$$

Where the maximum population growth rate is defined as $r_{max} = birth(t) * (1 - \frac{|P_f - P_m|}{P}) \ - \ d$, $H_{buck_n}(t, m, hbr)$ and $H_{doe_n}(t, m, hdr)$ represent district specific seasonal buck and doe hunting functions where n $\in [1, 2, 3, 4, 5, 6]$, and birth(t) represents the population birth rate at any given time t (in days). For further detail on how each function was defined, please reference this shared GitHub repository [link] [6] where we have uploaded a Jupyter Notebook containing our implementation for modeling the deer population in District 1.

3.1 Modeling Procedures

In the interest of time, we first defined a set of input parameters, for our model, that are derived with respect to the observed deer mortalites, as a result of hunting, from District 1. We believed this was a fair generalization method for modeling the deer population dynamics throughout all six districts because the observed deer mortalites, as a result of hunting, were approximately equally split among each district meaning that the total deer population is approximately equally distributed throughout West Virginia. The table below contains a set of standard input parameter values that we will use throughout our analyses.

Parameter	Value
P	550000
K	700000
C	8000
d	.2
m	.18
rf	.6-1
pr	.2
bsr	.78-.98
dsr	.77-.97

Figure 6: Table of standard model input parameters

Next, we defined a set of dynamic variables that we suspected were responsible for the majority of the resulting variation observed in the population system behavior over time. It is incredibly difficult, arguably impossible, to estimate a representative total deer population and, even more difficult, an accurate doe-to-buck population split. However, we know, from the observed hunting ratios and consulting wildlife experts, that the doe population tends to be larger than the buck population; so, we vary initial sex ratio splits accounting for this and our estimated carrying capacity **(K)**. Second, from a state regulatory point of view, varying hbr and hdr seemed to be the most controllable parameters when licensing for hunting permits.

Parameter	Value
P_f	275,000 - 500000
P_m	100,000 - 275000
hbr	0-1
hdr	0-1

Figure 7: Table of dynamic model input parameters

Finally, given our standardized and dynamic model inputs, we focused on three likely initial doe - buck population split hypotheticals for District 1: 1:1, 5:1, and 3:2 that all fall within the buck and doe population ranges from Figure 7. We aim to run through this series of initial population states to identify a set of parameters that will allow the deer population to survive for at least 100 years. We define this favorable population survival goal as the "hundred year herd".

When modelling for each hypothetical, we start each multi-year simulation on the first day of each year, ignoring the extra days from leap years. Within each annual cycle we calculate population change on a day-to-day granularity. The daily population change is primarily affected by dynamic seasonal birthing and hunting rates. Daily deer hunted and born are calculated using custom time dependent functions. The birthing rate function ensures an 85% population growth rate within any given year in an unrestricted and unconstrained environment where more deer are born in Spring and Summer months. The hunting functions calculate daily deer death according to seasonal hunting rates, the hunting quota as a percentage of the total deer population in District 1 (**m**), the ratio of does to bucks hunted (**hdr** and **hbr**), and the total deer population in District 1 at any given time (**P**).

In addition, we included complications to the models that contribute to the net daily death of the total deer population. The first complication accounts for change in the natural seasonal dependant survival rate of the doe and buck population, (**bsr** and **dsr**) where the deer are generally more likely to survive in Spring and Summer months and bucks are generally more likely, than does, to survive throughout the year. The second complication accounts for the passive deaths observed throughout the year that result from DVC's (**C**), this value is held at a constant throughout the year and relies on the third complication for rate limiting effects. The third complication accounts for the change in deer roaming behavior (**rf**) where we assume that deer are generally more active in Spring and Summer months, because of favorable weather conditions for roaming, which would lead to greater deer vehicle interactions that could result in more DVC's.

4 Results and Analyses

4.1 1:1 Doe - Buck Population Split

Projecting total deer population growth from initial conditions (18% hunting quota, 60% hunting buck ratio, both sexes start at 55,000) produces an unstable outcome marked by the male population continuously declining to 0 after 31 years. Despite the female population growing continuously for 21 years to 100,000, the 18% hunting ratio with 60% male proportion proved too high for the population to survive. By altering the sex proportions, there are stable population conditions that endure for 100 years if the male hunting ratio stays between 30% and 45%; all other proportions result in extinction. Only conditions between 30% and 35% produce total populations equal or greater than the starting level. Does increase over 100 years when the buck proportion is 40%-45% while bucks require 30% for population growth. A 35% hbr results in a steady population level for both sexes.

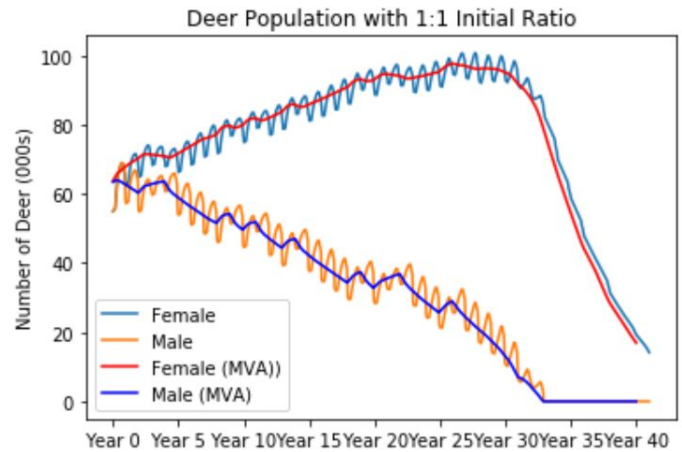

Figure 7: Plot of Baseline Initial Conditions Outcomes

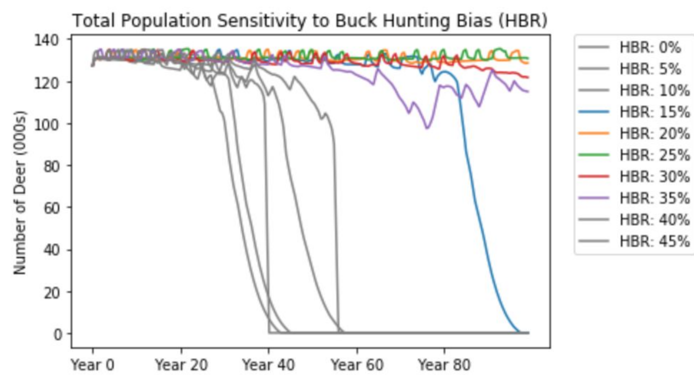

Figure 8: Examine herd survival sensitivity to hunting bias

4.1.1 Dampening Hunting Quota Every 2 years

Altering the hunting ratio every 2 years to 3-5% (from 18%), all else equal, results in an unstable population that lasts for 72 years. Prior to collapse, the population was approximately 120,000 with the male/female populations at a 10:2 proportion. The female population had grown steadily from 55,000 to 100,000. Despite lowering the hunting limit biennially, the male population declined from the onset and resulted in extinction. Altering the quota every 2 years between 3-5% can produce 100 year stable populations with buck hunting ratios between 20%-40%. Each of those sustainable total populations remain steady throughout the projection. Does increase in population between hbr levels of 40%-50%, stagnate within 30%-35%, and decline between 20%-25%. Bucks increase between 20%-35% but decline between 40%-50%. 30-35% hbr produces the most equal and steady population projection with both sexes ending between 60,000-70,000.

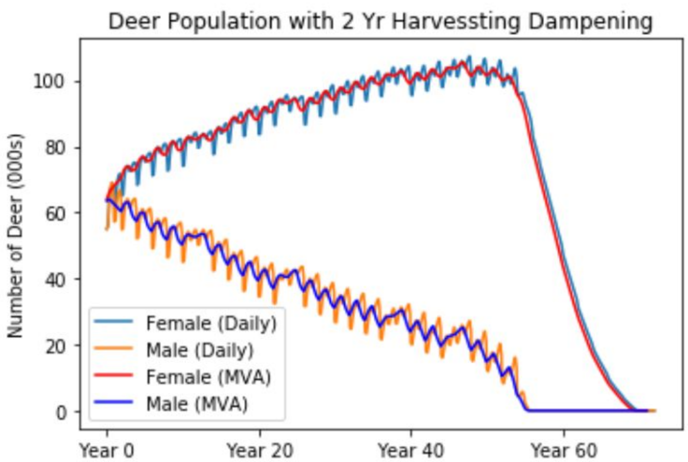

Figure 9: Herd survival with 2Yr Harvesting Dampening

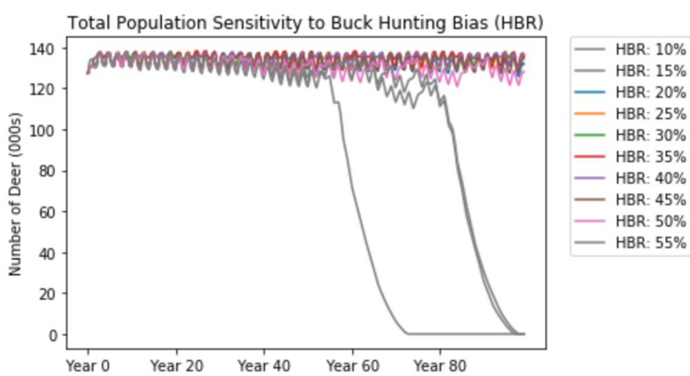

Figure 10: Examine herd survival sensitivity to hunting bias with 2Yr Harvesting Dampening

4.1.2 Dampening Hunting Quota Every 5 years

Adjusting the hunting ratio every 5 years to 3-5% (down from 18%), all else equal, provides greater longevity for the deer but also results in extinction. Under these conditions, the population lasts 43 years before the population descends to 0. Similar to the 2 year dampening, females grew consistently to 100,000 prior to the male population fall. Adjusting the sex propotion yields a narrow band of 100 year stable conditions between 25% and 40% hbr. 30%-35% ratios result in total population stability while 35%-40% result in moderate declines. A 30% hbr produces the most stable and equal population level for does and bucks with both ending at approx 60,000. 35%-40% ratios result in female population growth with male decay while 30% results in male population growth with female stagnation.

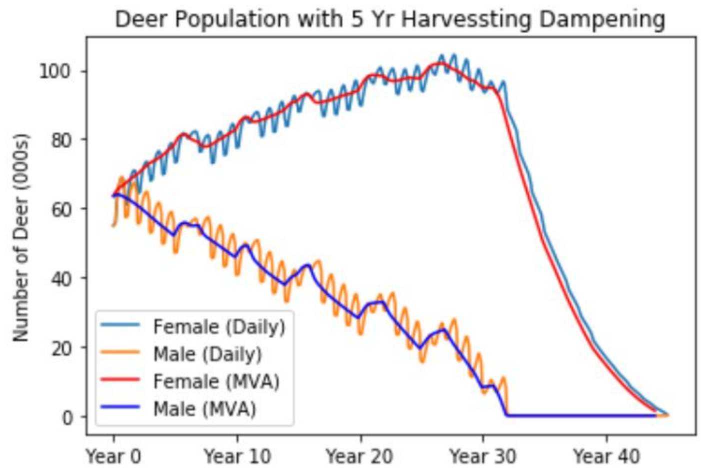

Figure 11: Herd survival with 5Yr Harvesting Dampening

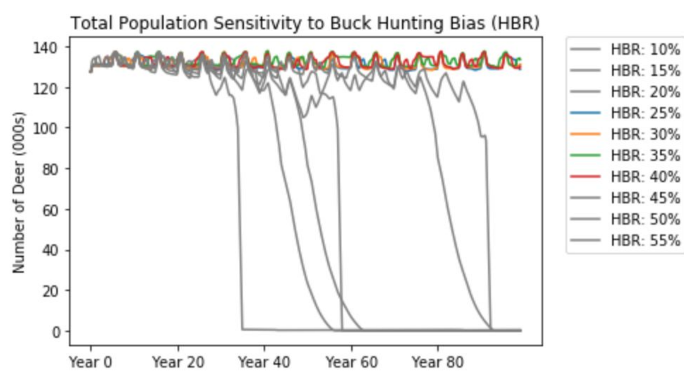

Figure 12: Examine herd survival sensitivity to hunting bias with 5Yr Harvesting Dampening

4.1.3 100 Year Herd Analysis

In order to achieve a 100 Year Herd for our baseline population ratio, we would need to adjust both our buck hunting bias as well as our overall annual harvest percentage. We would need to decrease our buck hunting bias ratio by 25 percentage points to get to our minimally viable 100 Year Herd and not more than 45 percentage point else our herd population quickly falls to zero before year 80. Additionally, we would need to deploy our 2-year harvest dampening strategy reducing harvest mortality by 80% every other year (effectively reducing annual harvest mortality to just under 11%).

4.2 4:1 Doe - Buck Population Split

In this scenario, the deer population changes to a 4:1 doe to buck ratio, while maintaining an 18% hunting quota with a 60% hunting buck ratio. The female population begins at 88,000 and the male population begins at 22,000. Under these conditions, the deer population is unsustainable and falls to 0 by 23 years. To attain a 100 year herd projection, the hbr proportions must decrease from 60% to between 25%-35%. Within this, 30%-35% result in static population levels while 25% results in a population decline. Does increase between 40%-45%, stagnate at 35%, and decline below 30% hbr. Bucks increase at 30%, stagnate between 35%-40%, and decline at 45% hbr.

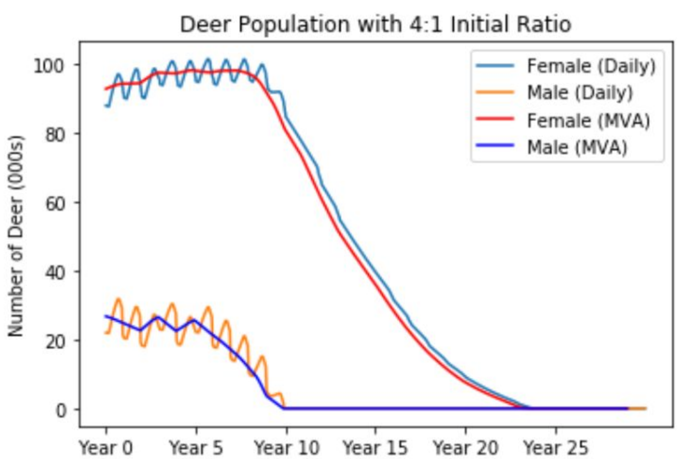

Figure 13: 4:1 Initial Population Ratio Outcomes

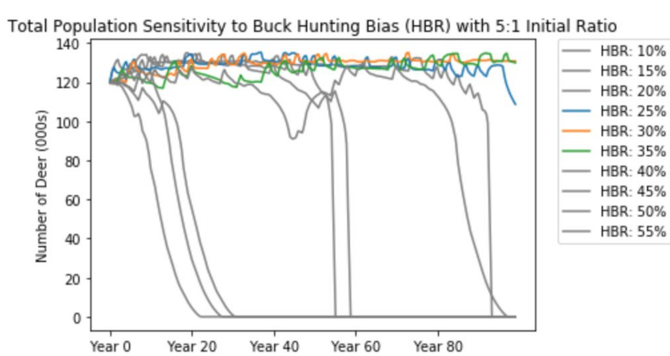

Figure 14: Examine herd survival sensitivity to buck hunting bias with 4:1 Initial Ratio

4.2.1 Dampening Hunting Quota Every 2 years

Modifying the hunting quota from 18% to between 3%-5% every 2 years produces a herd that lasts for 33 years, a 39 year decline from the same scenario for parity (4.1.1) Does top out at 100,000 within 10 years, flatline until 20 years, then plunge after the buck's gradual population decline towards 0. Does last roughly 10 years after the last buck dies. hbr levels between 10%-50% produce 100 year herds with only those near 10% causing population decline as all other ratios maintain population. Within the 100 year herd, does increase between 40%-50%, stagnate between 30%-35%, and decline between 15%-25%. Bucks increase between 15%-35%, stagnate at 40%, and decline between 45%-50%.

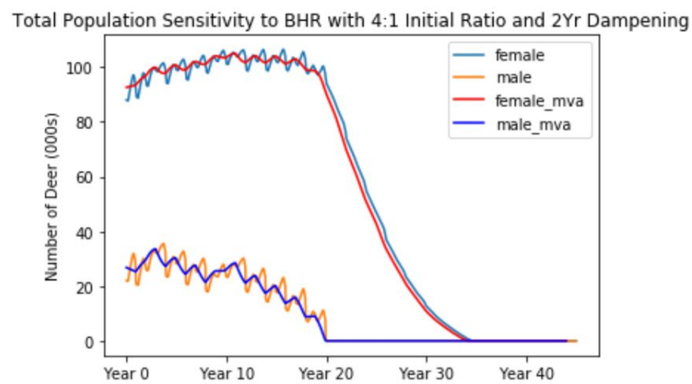

Figure 15: 4:1 Initial Population Ratio Outcomes with 2-Year Harvest Dampening

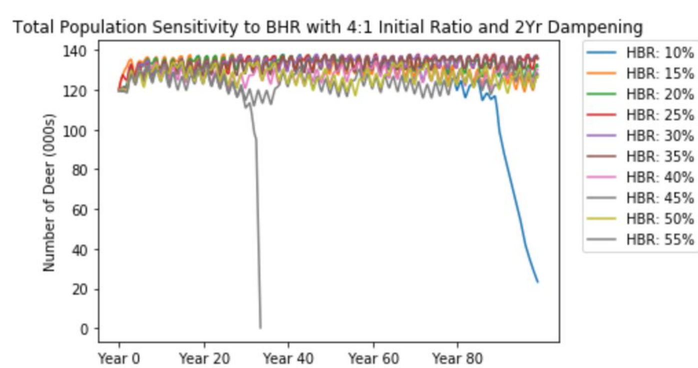

Figure 16: Examine herd survival sensitivity to buck hunting bias with 4:1 Initial Ratio

4.2.2 Dampening Hunting Quota Every 5 years

Altering the 4:1 population to a 3%-5% hunting quota (down from 18%) every 5 years results in an unsustainable herd that lasts for 23 years. This is a 13 year decline in life expectancy relative to the same management style in the 1:1 doe to buck ratio (4.1.2). Altering the hbr to rates between 25%-35% produces 100 year herds all while maintaining population levels over time. Does increase at 40%, stagnate between 30%-35%, and decline at 25%. Bucks grow at 25%, stagnate between 30%-35%, and decline at 40%.

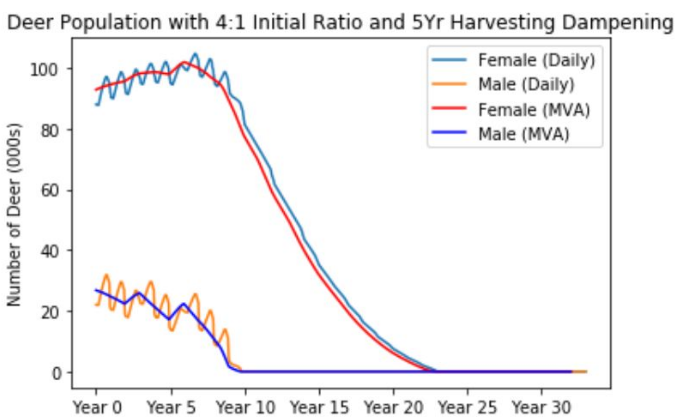

Figure 17: Herd survival with 5Yr Harvesting Dampening with 4:1 Initial Ratio

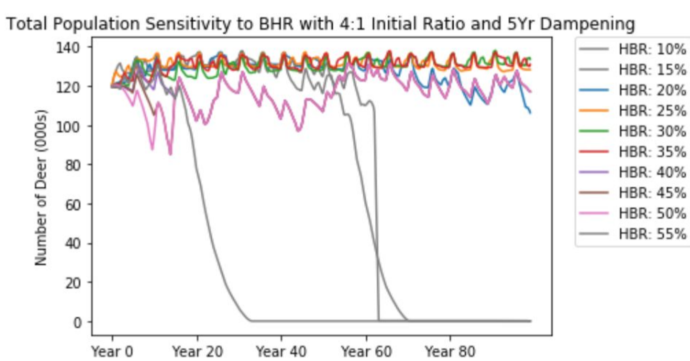

Figure 18: Examine herd survival sensitivity to hunting bias with 4:1 Initial Ratio and 5Yr Harvesting Dampening

4.2.3 100 Year Herd Analysis

In order to achieve a 100 Year Herd for our 4:1 population ratio, we would need to adjust both our buck hunting bias as well as our overall annual harvest percentage. We would need to decrease our buck hunting bias ratio by 7 percentage points to get to our minimally viable 100 Year Herd. Unique to the 4:1 hypothetical, there is no maximum adjustment recommended. That is, even at hbr = 0 where we exclusively hunt antlerless deer, the 100 Year Herd is still viable given we also deploy our 2-year harvest dampening strategy reducing harvest mortality by 80% every other year (effectively reducing annual harvest mortality to just under 11%).

4.3 3:2 Doe - Buck Population Split

In this scenario, the deer population alters to a 3:2 doe to buck ratio while maintaining an 18% hunting quota with a 60% hunting buck ratio. The female population begins at 66,000 and male population begins at 44,000. Under these conditions, the deer population lasts 6 years longer than the 1:1 ratio (4.1) at 37 years. Similar to parity, the female population increases to 100,000 before descending to 0 as a result the male population's persistent decline. While the initial condition was unstable, adjusting the hbr between 30%-45% supports a 100 year herd albeit with no growth scenarios. Ratios between 30%-40% maintain existing population levels and 45% decreases. For doe, 40%-50% hbr allows for growth, 30%-35% stagnancy, and 15%-25% decay. Bucks have a larger growth band from 15%-35%, decay from 45%-50%, with stagnant levels in between.

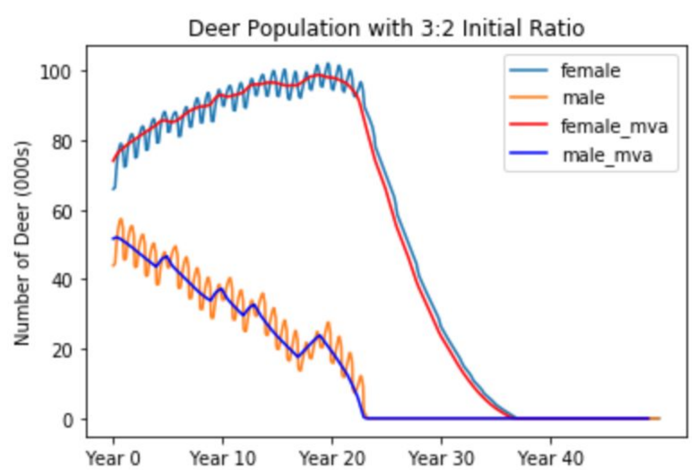

Figure 19: 3:2 Initial Population Ratio Outcomes

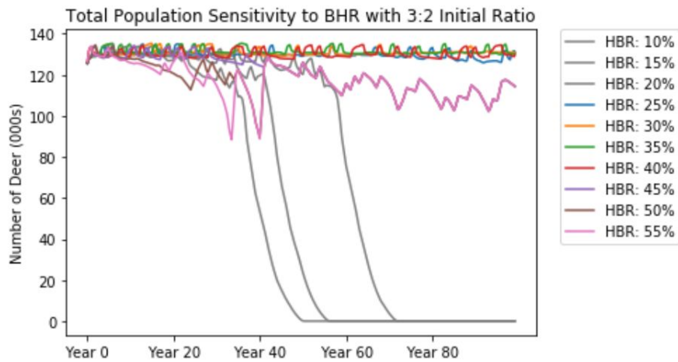

Figure 20: Examine herd survival sensitivity to buck hunting bias with 3:2 Initial Ratio

4.3.1 Dampening Hunting Quota Every 2 years

Dampening the hunting quota to 3%-5% (from 18%) every 5 years results in a population that lasts over 65 years. Similarly to the base scenario, females grow steadily to 100,000 over 50 years then decline for 10. Bucks decline gradually for 20 years, pick up for about 10 years then decline after 40 years. This projection is 7 years less than 1:1 but 22 more than 4:1. An hbr rate between 15%-50% causes 100 year herds. Within that band, 20%-45% maintain starting populations while the periphery figures result in slight decline. Does increase between 40%-50%, stagnate between 25%-30%, and decline between 15%-25%. Bucks increase between 15%-35%, stagnate through 40%, and decline between 45%-50%.

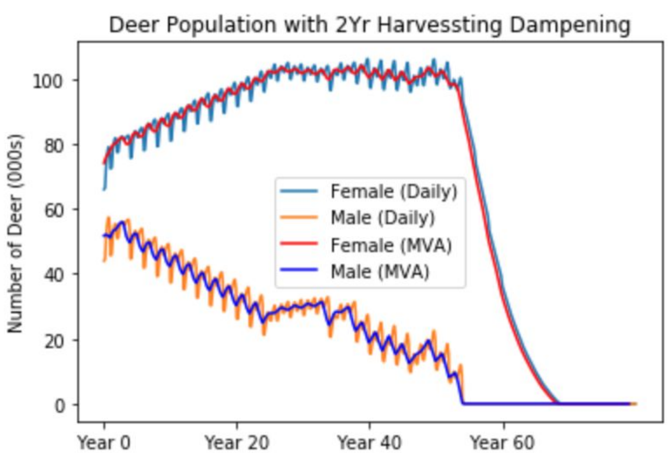

Figure 21: 3:2 Initial Population Ratio Outcomes with 2-Year Harvest Dampening

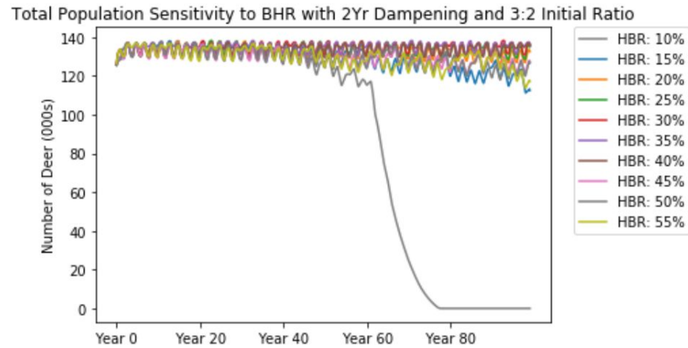

Figure 22: Examine herd survival sensitivity to buck hunting bias with 3:2 Initial Ratio

4.3.1 Dampening Hunting Quota Every 5 years

Dampening the hunting quota to 3%-5% (down from 18%) every 5 years results in a population that lasts for approximately 45 years. This result is the longest life expectancy of all 5 year management scenarios. Females grow steadily to 100,000 over 50 years. In contrast, the males descend to half their starting population levels after 20 years then enter a concave decay trajectory until the 55 years. Altering the hbr between 25%-40% yields 100 year herds with population stability between 30%-40% and decline between 25%-30%. Within those herds, does increase only at 40%, stanate between 25% and 30%, and decline below 20%. Bucks increase between 25%-35% and stagnate near 40%.

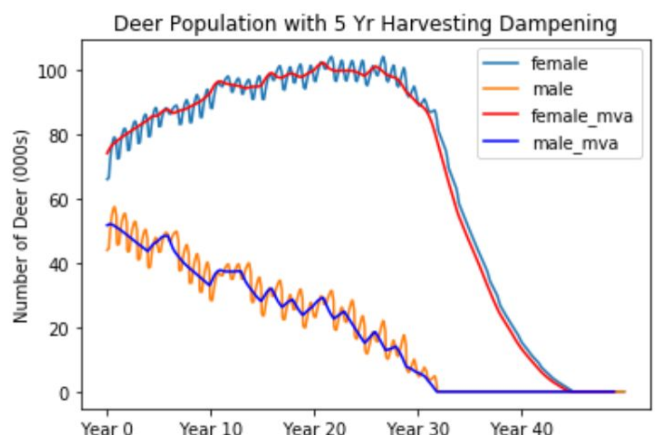

Figure 23: Herd survival with 5Yr Harvesting Dampening with 3:2 Initial Ratio

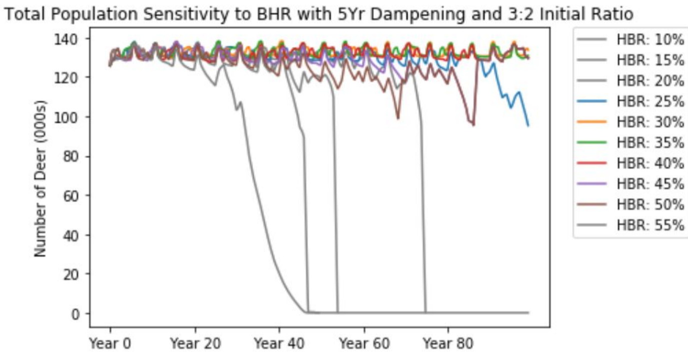

Figure 24: Examine herd survival sensitivity to hunting bias with 3:2 Initial Ratio and 5Yr Harvesting Dampening

4.3.2 100 Year Herd Analysis

For our 3:2 population ratio, in order to achieve a 100 Year Herd, we would need to adjust both our buck hunting bias as well as our overall annual harvest percentage. We would need to decrease our buck hunting bias ratio by 14 pct points to get to our minimally viable 100 Year Herd and not more than 45 pct point else our herd population quickly falls to zero before year 80. Additionally, we would need to deploy our 2-year harvest dampening strategy reducing harvest mortality by 80% every other year (effectively reducing annual harvest mortality to just under 11%).

4.4 Results Summary

4.4.1 Average Life Expectancies

The 3:2 and 1:1 doe to buck ratio tied for the highest average longevity among all 3 groups at 49 years apiece. The 4:1 was 24 years shorter on average at 22 years. The average life expectancy across all ratios was 41. In every scenario, 4:1 had the shortest life cycle. These figures suggest a slight, but not extreme, starting bias towards does produce the highest expected survival rates.

The results also indicate greater longevity when introducing management techniques. Resetting the hunting quota every 5 years to 3%-5% from 18% results in a 20% increase in average life expectancy from 30 to 36 years. Moreover, resetting every 2 years reaps a 76% increase in average expectancy from 30 to 53 years.

Average values across ratio or management were not proportional in all cases. For example, the 4:1 initial condition had a 3 year longer life cycle than the 5 year dampening of the same ratio. This provides further evidence of the superiority of the 2 year dampening.

In terms of average temporal superiority, the 1:1 and 3:2 ratios differ depending on dampening tactic. Our results suggest that if the WVDNR preferred a passive approach (no dampening or 5 year dampening), a 3:2 doe to buck ratio would be preferable. However, if the department wants an active approach and to achieve optimal lifetime levels (within constraints of this exercise), it should dampen every 2 years within the 1:1 ratio.

Doe:Buck	Initial	5 Year	2 year	Average
1:1	31	43	72	**49**
4:1	23	20	33	**25**
3:2	37	45	65	**49**
Average	**30**	**36**	**53**	**41**

Figure 25: Table of average life expectancies by dampening type and doe to buck ratio

4.4.2 100 Year Herds

The 100 year herd projection is achievable by lowering the hbr thresholds from 60% since no projection at that level lived past 72 years. Depending on the scenario, hbr's as low as 10% and as high as 50% produce sustainable populations. Each projection produced hbr ranges, the size of which varies each with different implications. On average, the 2 year dampening had the highest range of sustainable hbr levels at a spread of 35pp (22pp higher than both the initial and 5 year dampening conditions). The 2 year features the highest spread in every sex scenario.

As above 60%, hbr below 10% never produces 100 year herds. Compared to management style, variance is lower by doe:buck ratios. Of the three ratios, 4:1 had the largest sustainable hbr range at 23pp, slightly higher than 3:2's 22pp, followed by the parity case 17pp.

Similar to life expectancy, the highest overall average hbr range is not the greatest value in all cases. For example, the lowest average hbr range proportion, 1:1, is tied for the highest range in both the initial condition and 5 year dampening.

Having a higher hbr range provides flexibility in the rate of buck hunting to produce a 100 year herd. However, since 50% is the highest hbr rate possible, a large range implies larger deviations from the current hbr.

In general, a higher doe to buck ratio depresses the hbr needed to achieve 100 year herd levels as the population becomes more sensitive. For example, the 4:1 ratio has the lowest average hbr at 30%. This does not hold true consistently: the 3:2 ratio has the largest range but also the highest average and max hbr.

Doe:Buck	Initial	5 Year	2 year	**Average**
1:1	15	15	20	**17**
4:1	10	10	50	**23**
3:2	15	15	35	**22**
Average	**13**	**13**	**35**	**21**

Figure 26: hbr percentage point ranges that lead to viable 100 Year Herds per initial population ratio and harvest dampening strategy

max				
Doe:Buck	Initial	5 Year	2 year	**Average**
1:1	45	40	40	**42**
4:1	35	35	50	**40**
3:2	45	40	50	**45**
Average	**42**	**38**	**47**	**42**
min				
1:1	30	25	20	**25**
4:1	25	25	0	**17**
3:2	30	25	15	**23**
Average	**28**	**25**	**12**	**22**

Figure 27: hbr min and max contributing to percentage point ranges calculated in Figure 26

4.4.3 Recommended Strategies

To achieve the 100 year herd within the limitations of this study, this paper encourages WVDEN to set the goal of reducing hbr to between 30-45% from 60%. No dampening is required so long as the doe to buck ratio stays between 1:1 and 3:2. The most significantly impactful measure would be to ensure a decrease in hunters' bias toward harvesting bucks by at least 15 percentage points. If *the gap in female to male populations increases beyond 3:2,* it may be necessary to further adjust the hbr. This recommendation accommodates the logistical realities of managing deer hunting rates.

5 Conclusion

Two parameters were initially suspected to be responsible for the greatest observable variation in total deer population behavior over time: initial deer population doe and buck ratio splits and buck hunting ratio. Through our analyses, we can note that slight adjustments in either parameter can heavily influence the long term behavior of a population system. However, it quickly became obvious that buck hunting ratio leads to the greatest system variability and is the most easily controllable parameter from a hunting regulation point of view.

Lowering the hunting mortality rate to 3%-5% every 2 and 5 years respectfully while modifying the starting population proportions would still lead to extinction if hbr remains at or above 60%. Yet, in every hypothetical respective to each do-buck split, adjusting the hbr to a lower range, while all other parameters held constant, produced 100 year herds.

If the hunting buck ratio is strictly bound to 60 percent due to socio-economic reasons, the population will go extinct in less than 100 years. The best case is to maintain sex parity with a 2 year dampening reducing the hunting levels to 3%-5%.

If not bound to a 60% hbr, WVDNR can both adjust the hbr and instil dampening within each doe to buck breakdown. Decisions altering hunting methods depend on ability and willingness among stakeholders. For example, if hunters prefer to maintain hbr levels closest to the current 60%, 2 year dampening is required to achieve maximum hbr values of 40%-50% which will ensure a 100 year herd.

6 Individual Contributions

All team members equally contributed to formulating the scope of the project, fine-tuning the models and methodologies, constructing the final paper, and documenting their respective contributions throughout. Tigran designed and implemented the conceptual deer population model diagram, the initial set of ordinary differential equations used to model the deer population, and all other time dependent functions. Adrian performed the primary exploratory analysis to identify viable data sources and project directions as well as curating and publishing the visualizations. Adrian and Louis met with domain experts to better understand the current herd condition as well as harvesting and data collection strategies. Louis transcribed results, analyzed model projections, and provided optimal deer population recommendations.

7 Acknowledgements and References

[1] Bailey, R. 2001. “North America's most dangerous mammal”. *Reason Online*, https://reason.com/2001/11/21/north-americas-most-dangerous/

[2] *West Virginia Division of Natural Resources*, www.wvdnr.gov/.

[3] Brandon M. Hale and Maeve L. McCarthy, "An Introduction to Population Ecology - The Logistic Growth Equation," Convergence (October 2005)

[4] M.S. Boyce, K. Knopff, J. Northrup, J. Pitt and L.S. Vors, Harvest models for changing environments, in Wildlife Conservation in a Chang-ing Climate, University of Chicago Press, 293-306 (2012).

[5] Big Game Bulletin 2019. http://www.wvdnr.gov/hunting/PDFFiles/BGB_2019.pdf

[6] Jupyter Notebook Github repository: https://github.com/TMALLC/Modeling-Deer-Population-Control-System-Dynamics

We would like to thank West Virginia State Trooper Seth Cook and WVDNR Assistant Chief Scott Warner for their invaluable help in defining accurate initial deer population estimates and developing our system of ODE’s .