APPENDIX B. FINAL REPORT POINT REYES FALLOW DEER MODELING

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Modeling Objective

I constructed a stage-based simulation model following Hobbs et al. (2000) to examine the effect of culling and fertility control on the abundance of fallow deer in Point Reyes National Seashore. Specific questions to be addressed by the model included:

1) How many animals must be culled or treated with contraceptives to eradicate the population?
2) Does fertility control offer a feasible alternative to culling as a way to eliminate fallow deer?
3) Can fertility control increase the efficiency of culling in an eradication campaign?
4) How does the duration of effect of contraception influence the number of animals that must be treated or culled to achieve eradication?

Model Structure

Overview

The model represents 2 sexes and 3 age stages, juveniles, yearlings and adults. The number of stages was chosen to represent important differences in survival and fertility and to facilitate comparison with field observations where no more than two ages can be identified. Census occurs in January and most mortality is assumed to occur between census and births (Figure 1). A birth pulse occurs during May, followed by breeding in late October. Thus, juveniles are 8 months old at the time of census. I assume that treatment with contraceptives occurs after births but before breeding. The model consists of linked difference equations and represents annual changes in abundance of animals in each stage (Figure 2) at a one year time step. Simple variations in model structure allow it to represent fertility control agents differing in duration of efficacy.

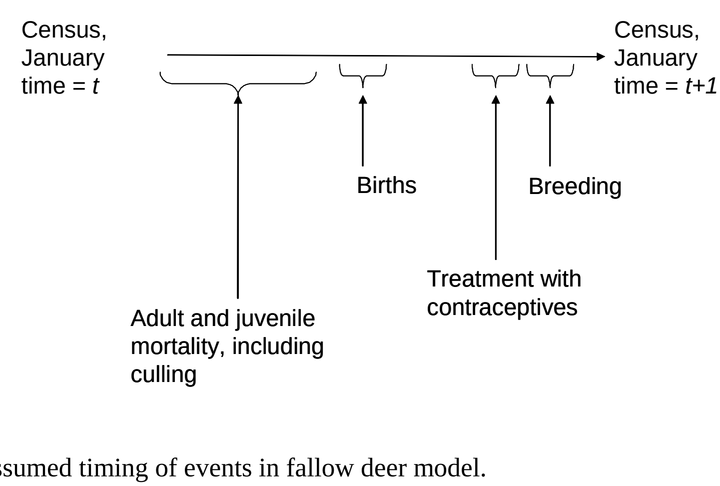


Figure 1. Assumed timing of events in fallow deer model.

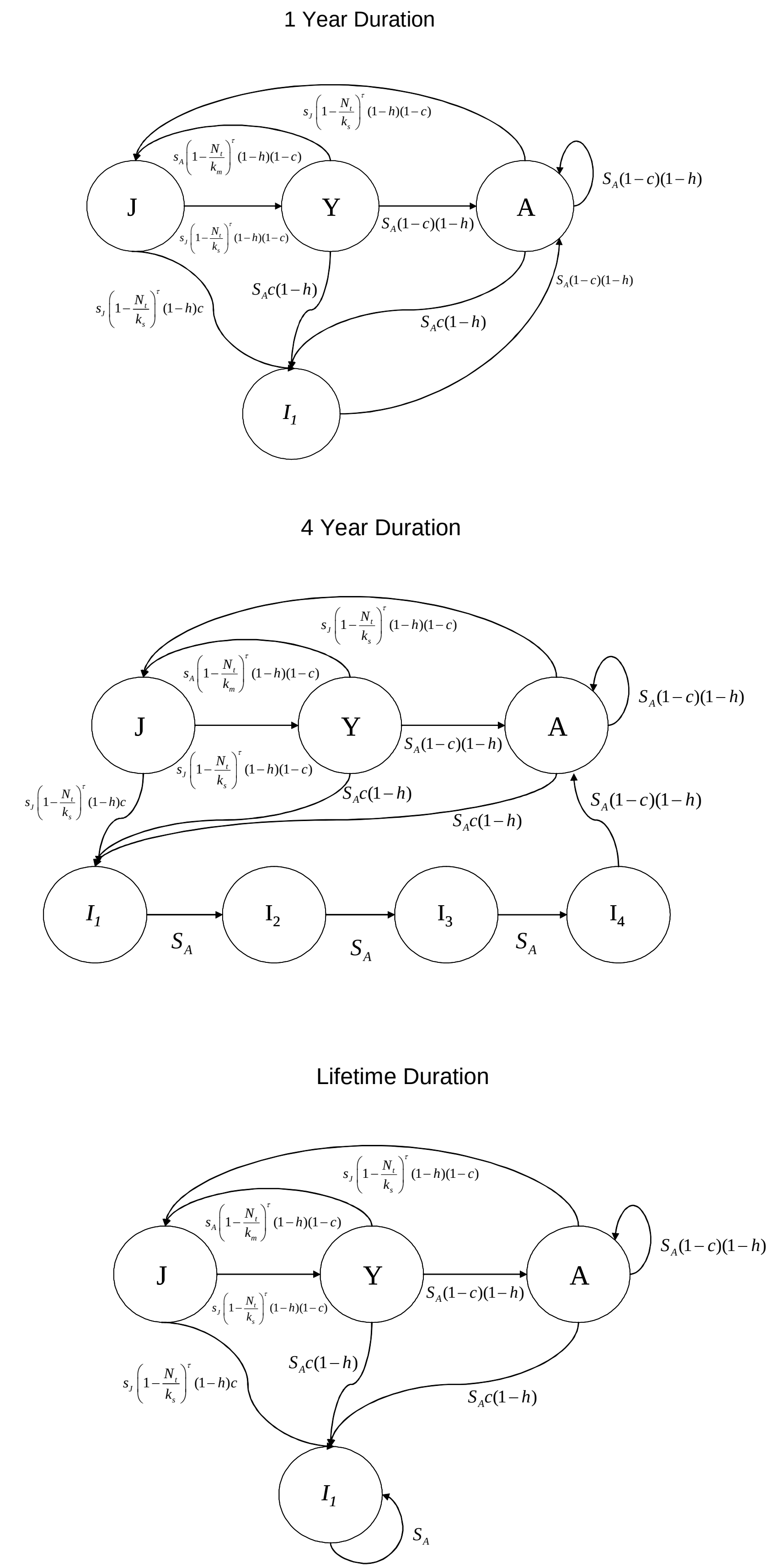


Figure 2. Structure of models used to represent effects of culling and fertility control on fallow deer populations in Point Reyes National Seashore. Duration refers to the length of time fertility control agents remain effective following treatment. See Table 1 for definitions of parameters. See text for definitions of state variables.

Model Parameters

Models include 7 parameters and two decision variables (Table 1). These are tabulated here to facilitate understanding the equations that follow. In a subsequent, section, I describe procedures for estimating parameter values.

Table 1. Values and definitions for parameters used in Fallow Deer model.

Parameter	**Value**	**Definition**
m_A	.9	Maximum per capita rate of recruitment by adult females occurring when population size is close to 0. This recruitment rate specifies the number of offspring that survive to the first census produced per adult female alive at the birth pulse.
m_Y	.5	Maximum per capita rate of recruitment by yearling females occurring when population size is close to 0. This recruitment rate specifies the number of offspring that survive to the first census produced per yearling female alive at the birth pulse.
k_m	1500	The population size at which no offspring survive from birth to census.
r	.5	Sex ratio of offspring
s_J	.9	Maximum survival of juveniles. Juvenile survival is defined as the proportion of juveniles alive at census at time *t* that survive to become yearlings at time *t+1* and, thus, represents survival from age 8 to 20 months. The maximum value occurs when total population size is near 0.
s_A	.9	Adult survival rate, assumed to be constant.
k_s	3600	The population size where juvenile survival rate reaches a minimum value, assumed to be .10.
τ	1	Shape parameter controlling the abruptness of density dependence. As τ approaches 0, effects of density are not seen until large population sizes.
Decision Variables		
h	Specified by user	Culling rate, the number of animals that are culled during time t to t+1 divided by the number of animals that escape natural mortality during time t to t+1
c	Specified by user	Treatment rate, the number of animals treated with contraceptives during time t to t+1 divided by the number of animals that escape culling and natural mortality.

Model Formulation

The equations composing the 4 year duration fertility control model are outlined below in a form that isolates terms for the number of animals culled and treated with contraceptives. Formulating them this way leads to expressions that are not as compact as they could be, but which should be more easily understood than if I wrote equations in their simplest, most reduced form. Equations for the lifetime and single year duration models are variations of the 4 year case and will be described following the development of the 4 year model.

I first define a recruitment function, $f(Y_t, A_t, N_t)$ to estimate the number of fawns that are alive at their first census. This function represents fertility, the number of offspring born per female in the population, as well as survival during the animals first 7 months. I predict recruitment using,

$$f(Y_t, A_t, N_t) = s_A(Y_t m_Y + A_t m_A)\left(1 - \frac{N_t}{k_m}\right)^{\tau} \qquad (1)$$

where t index time, Y_t is the number of yearling females at time t, A_t is the number adults at time t and N_t is total population size at time t. Adult survival is included in the recruitment function because adults must survive from census to births to contribute offspring at the next time step. To achieve a simple formulation, I assume that density affects the number of offspring produced by adults and yearlings in a similar fashion, but that adults produce more offspring than yearlings when density is low. The parameter τ controls the way that recruitment rate responds to density. When τ is 1, then the per capita recruitment rate declines linearly with increasing population size, which is the usual logistic assumption. When τ approaches 0, recruitment remains insensitive to changes in population numbers until high densities are reached (Figure 3) This parameter is included for sensitivity and uncertainty analysis because the shape of the relationship between density and recuritment is not known.

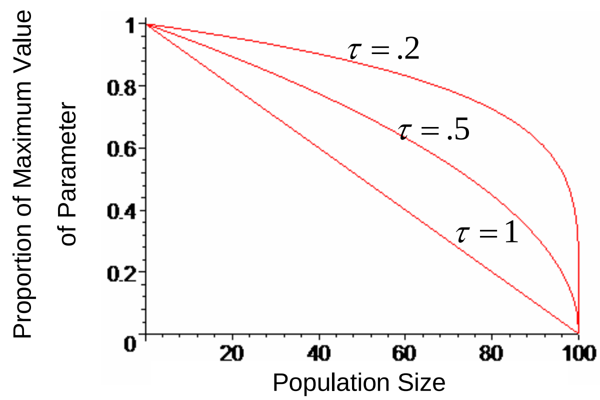


Figure 3. Illustration of model representation of non-linear density dependence for a hypothetical population with carrying capacity = 100 animals.

Dynamics of fertile females are specified by:

$$J_{t+1} = f(Y_t, A_t, N_t)r - H_{Jt} - C_{Jt}$$
$$H_{Jt} = f(Y_t, A_t, N_t)rh$$
$$C_{Jt} = f(Y_t, A_t, N_t)r(1-h)c$$

$$Y_{t+1} = J_t s_J\left(1 - \frac{N_t}{k_s}\right)^{\tau} - H_{Yt} - C_{Yt}$$

$$H_{Yt} = J_t s_J\left(1 - \frac{N_t}{k_s}\right)^{\tau} h \qquad (2)$$

$$C_{Yt} = J_t s_J\left(1 - \frac{N_t}{k_s}\right)^{\tau} (1-h)c$$

$$A_{t+1} = (A_t + Y_t)s_A - H_{At} - C_{Yt} + s_A(1-h)(1-c)I_{4t}$$
$$H_{At} = (A_t + Y_t)s_A h$$
$$C_{At} = (A_t + Y_t)s_A(1-h)c.$$

The state variable J_t represents the number of female fawns at time t. The state variable I_{4t} gives the number of animals treated with finite duration contraceptives that would have become fertile in the absence of treatment. The decision variable H specifies the number of animals culled from the population during time t to $t+1$,while the decision variable C gives the number of animals treated with contraceptives during that interval. Subscripts on these terms index the stage (juvenile, yearling, adult) and the year. So, for example, C_{At} gives the number of adult females that are treated with contraceptives during time t to $t + 1$.

Dynamics of the male portion of the population resemble those of the females:

$$\begin{aligned} J'_{t+1} &= f(Y_t, A_t, N_t)r - H_{J't} \\ H_{J't} &= f(Y_t, A_t, N_t)(1-r)h \\ Y'_{t+1} &= J'_t s_J \left(1 - \frac{N_t}{k_s}\right)^{\tau} - H_{Y't} \\ H_{Y't} &= J'_t s_J \left(1 - \frac{N_t}{k_s}\right)^{\tau} h \\ A'_{t+1} &= (A'_t + Y'_t)s_A - H_{A't} \\ H'_{A't} &= (A'_t + Y'_t)s_A h. \end{aligned} \qquad (3)$$

Where each stage is as defined above, with ' indexing males.

If animals are treated with contraceptives then infertile females must be represented in the model. When the effect of contraceptives is permanent, the number of infertile animals (I_t) is the population is estimated as

$$I_{t+1} = \left[\left(1 - \frac{C_{Jt}}{I_t}\right)s_A + \frac{C_{Jt}}{I_t}\left(1 - \frac{N_t}{k_s}\right)^{\tau} s_J\right] I_t + C_{Jt} + C_{Yt} + C_{At} . \qquad (4)$$

Where I_t is the number of infertile females at time t and the C's give the number of animals treated in each age class during time t to $t + 1$. Note that this formulation accounts for difference in survival between juveniles and yearlings/adults by weighting the survival rate of juveniles and older animals by their proportions in the infertile stage.

When the effects of contraceptives are temporary, then we must keep track of the time since the animal was treated. This is done as follows:

$$
\begin{aligned}
I_{1,\,t+1} &= C_{Jt} + C_{Yt} + C_{At} + C_{I_4 t} \\
I_{2,\,t+1} &= I_{1,\,t}\left[\left(1-\frac{J_t}{N_t}\right)s_a + \frac{J_t}{N_t}s_{Jt}\left(1-\frac{N_t}{k_s}\right)^{\tau}\right] - H_{I_1 t} \\
H_{I_1 t} &= I_{1,\,t}\left[\left(1-\frac{J_t}{N_t}\right)s_a + \frac{J_t}{N_t}s_{Jt}\left(1-\frac{N_t}{k_s}\right)^{\tau}\right]h \\
I_{3,\,t+1} &= I_{2,\,t}s_A - H_{I_2 t} \\
H_{I_2 t} &= I_{2,\,t}s_A h \\
I_{4,\,t+1} &= I_{3,\,t+1}s_A - H_{I_3 t} - C_{I_4 t} \\
H_{I_3 t} &= I_{3,\,t}s_A h \\
C_{I_4 t} &= I_{4t}s_A(1-h)c.
\end{aligned}
\qquad (5)
$$

I assume that animals that are infertile and will not become fertile during time *t* to *t+ 1* (i.e., $I_{1t,} I_{2t}, I_{3t}$) are not treated with contraceptives because treatment occurs every 4 years. Again, the *C's* give the number animals that are treated during time *t* to *t+1*. Each *C* is indexed by stage and time, so, for example C_{jt} gives the number of juveniles treated during time *t* to *t+1*. Note that $C_{I_4 t}$ gives the number of animals that were infertile at time *t* and that were prevented from becoming fertile at time *t+1* by treatment.

The total population size is the sum of the stages described above,

$$N_t = J_t + Y_t + A_t + J'_t + Y'_t + A'_t + \sum_{i=}^{4} I_{i,t}\ . \qquad (6)$$

The lifetime effect model eliminates 3 infertile stages, replacing them with a single stage that does not return to the fertile adult stage (Figure 2). The single year duration model is identical to the lifetime effects model except that all infertile animals that are not treated return to the fertile adult stage during each time step.

Estimating Model Parameters

Demographic data on the Point Reyes Fallow deer population lack detail and depth, and as a result, we must rely on coarse estimates of parameters to allow simulation of the population's dynamics. Because these estimates are imprecise it will be important to incorporate appropriate uncertainty in model predictions to reflect uncertainty in parameter estimates. Procedures for uncertainty estimation will be discussed in a later section; here I describe procedures for determining best, educated guesses at parameter values.

Parameters controlling density dependent relationships are the most difficult to estimate, but current data allow approximations. Staring with the density dependent relationship controlling recruitment, I estimated m_A and m_Y loosely from allometric relationships for reproductive rates of ungulates. The parameter k_s represents the population size at for which recruitment = 0. (Note that this is not the conventional definition of ecological carrying capacity, which is the population size at which $N_t / N_{t+1} = 1$. Instead, ecological carrying capacity in this model depends on the interplay between k_m and k_s.) We can approximate k_s as follows. We start with the expression for juvenile females, assuming linear density dependence (e.g, $\tau = 1$) and culling and contraception rates = 0:

$$J_{t+1} = s_A(m_A F_t + m_Y Y_t)\left(1-\frac{N_t}{k_m}\right) r\ . \qquad (7)$$

Dividing both sides by $s_a(F_t + Y_t)$ we obtain:

$$\frac{J_{t+1}}{s_A(F_t+Y_t)} = \frac{(m_A F_t + m_Y Y_t)\left(1-\frac{N_t}{k_m}\right)r}{(F_t+Y_t)}. \tag{8}$$

We don't know F_t or Y_t, but for the problem at hand, we simply need to know $\frac{Y_t}{F_{tt}}$. If we know the ratio of yearling females to adult females, in the population then we can scale the $F_t + Y_t$ term using that ratio by allowing F_t.=1. For example, if there are 25 yearling females per 100 adult females then the scaled sum of $F_t + Y_t$ is 1.25.

The left hand side of this expression is the ratio of juveniles (males and females) to surviving adult females, which is quite analogous to the fawn/doe ratios observed in the fall. Using the average ratios from the last 3 years (=.379), setting N_t = 800 based on the 2002 census, assuming that the sex ratio of offspring is .5, and risking the decidedly heroic assumption that half of the fawns observed in fall counts are female (i.e., J_{t+1} = fawn count/2) we obtain an equation with one unknown, k_m. Solving gives us k_m = 1487.

We can use similar logic to estimate k_s.. Assuming linear density dependence, the expression for juveniles surviving to become yearlings is

$$Y_{t+1} = J_t s_J \left(1-\frac{N_t}{k_s}\right), \tag{9}$$

which on rearrangement gives us the ratio of yearlings to juveniles at the time of census as a function of N_t and k_s:

$$\frac{Y_{t+1}}{J_t s_J} = \left(1-\frac{N_t}{k_s}\right) \tag{10}$$

I assumed above s_J = .90, which is a very reasonable guess for populations at low density. (Remember that s_J cannot exceed 1, so it's upper value is constrained.) Equipped with that informed guess and knowing the ratio of yearlings to juveniles at t and N_t from data we again arrive at an equation with a single unknown, k_s. Solving provides k_s = 3600. We would expect this value to be higher than k_m because recruitment to age 8 months in ungulates is likely to be much more sensitive to density than their survival thereafter.

Adult survival was assumed to be constant and high, an assumption that has strong support in data for ungulates in general, even if we lack those specific data for fallow deer at Point Reyes.

Management Scenarios

Model runs were designed to represent two management alternatives. The first alternative was to eradicate fallow deer from Point Reyes during the next fifteen years. The second alternative was to reduce the population to 350 animals, including 50 fertile females over the same time interval. For each of these alternatives, I also I evaluated 5 control scenarios: fertility control alone, culling alone, and culling combined with treatment of 25%, 50% and 75% of surviving fertile females with contraceptives. Within each of the fertility control scenarios, I evaluated effects of duration of contraceptives by assuming that a single dose rendered an animal infertile for its lifetime, for 4 years, or for a single year. Current contraceptive technology provides one year of infertility per dose, however, fertility control agents lasting 4 years and agents sterilizing the animal for life are likely to be available for research applications during the next 2 years.

I assumed that fertility control agents were delivered to all ages in the population every 4 years beginning at year 0. Culling was assumed to start in year 1. I evaluated two culling regimes, which I will refer to as Fertiles Only and Females Only. In the Fertiles Only culling regime, I assumed that that only fertile females would be culled during the first ten years of the simulation. This means that animals treated with contraceptives would be marked so that infertile animals and males would be recognizable and would *not* be culled. In the Females Only culling regime, I assumed that only females would be culled during the first 10 years of the simulation. This means that animals treated with contraceptives would not need to be marked and would be culled along with fertile animals. In both regimes, I assumed that culling became indiscriminate after year 10, allowing males as well as fertile and infertile females to be culled.

Simulated control regimes assumed that a fixed *proportion* of animals would be treated or culled annually, rather than a fixed *number* of animals. The primary motivation for this approach was to represent what could be realistically achieved with a fixed annual investment in control efforts. Given a fixed amount of time allocated to finding and treating or culling animals, the number of animals treated or culled will assuredly decline as the population size declines. This is the case because the encounter rate with deer will diminish as the population is reduced, requiring more investment of time per animal treated or culled. Control efforts aimed at a fixed proportion of animals provide a diminishing target number of animals as the population is reduced and in so doing accommodate the increased amount of time that must be invested per deer treated or culled.

I did not evaluate a purely indiscriminate culling regime where all sexes and ages were culled during all years because I assumed that culling males from the outset would diminish the density dependent effects of males on female reproduction and survival and, hence, would increase the number of animals that must be culled. This assumption was verified by preliminary simulations—approximately 30% more animals would need to be culled to eradicate the population if culling was not selective for females in the first 10 years of the eradication effort.

To evaluate efficacy of fertility control alone, I predicted the population size at the end of 15 years assuming that 75% of the females could be treated every 4 years, which was judged to be the maximum possible delivery rate given logistic and financial constraints.

Model Implementation

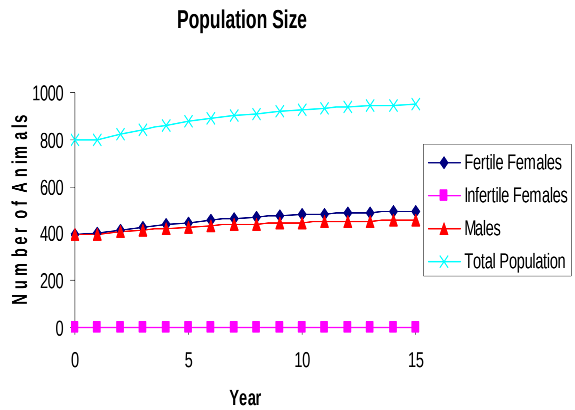
Equations outlined above were coded in Visual Basic for Applications running under Microsoft Excel. I used non-linear gradient search techniques to find culling rates that minimized the number of animals culled and treated with contraceptives subject to two constraints: that no more than half of the target population can be culled during any single year and that the population must number fewer than 5 animals 15 years after initiating treatment.

Results: Eradication Alternative

Population Trajectory in Absence of Control Efforts

Deterministic model runs in the absence of any culling or fertility control suggested that the current population is slightly below ecological carrying capacity and will continue to grow to a steady state of approximately 1000 animals (Figure 4). This estimate is reasonably close to the estimate obtained by (Gogan et al. 2001), and although both estimates could be wrong, it is reassuring that two different approaches to estimating carrying capacity yielded similar results.

It is imperative to understand that these results depend on the assumption that the Point Reyes fallow deer population is “closed” , which is to say that there is no emigration from the population to the surrounding area. This simplifying assumption is necessary to because we lack the data needed to model movement out of the park to the adjacent landscape. However, it is virtually certain that such movement would occur.



Effects of Fertiles Only Culling With and Without Fertility Control

Simulations of culling alone and culling in combination with fertility control indicated that the population could be eradicated within 15 years (Figure 5), but the effort required to achieve eradication differed among management scenarios. Culling alone required killing 653 animals over the course of the 15 year campaign (Figure 6). Combining culling with fertility control reduced the numbers of animals that would need to be culled, but increased the total number of animals that would need to be treated or culled (Figure 6). The extent of reduction in culling declined with declining duration of the contraceptives; the greatest reductions were achieved by delivering lifetime effect contraceptives. The smallest reductions occurred in simulations of single year duration contraceptives (Figure 6).

Figure 4. Trajectory of population growth of the Point Reyes fallow deer population in the absence of culling or fertility control.

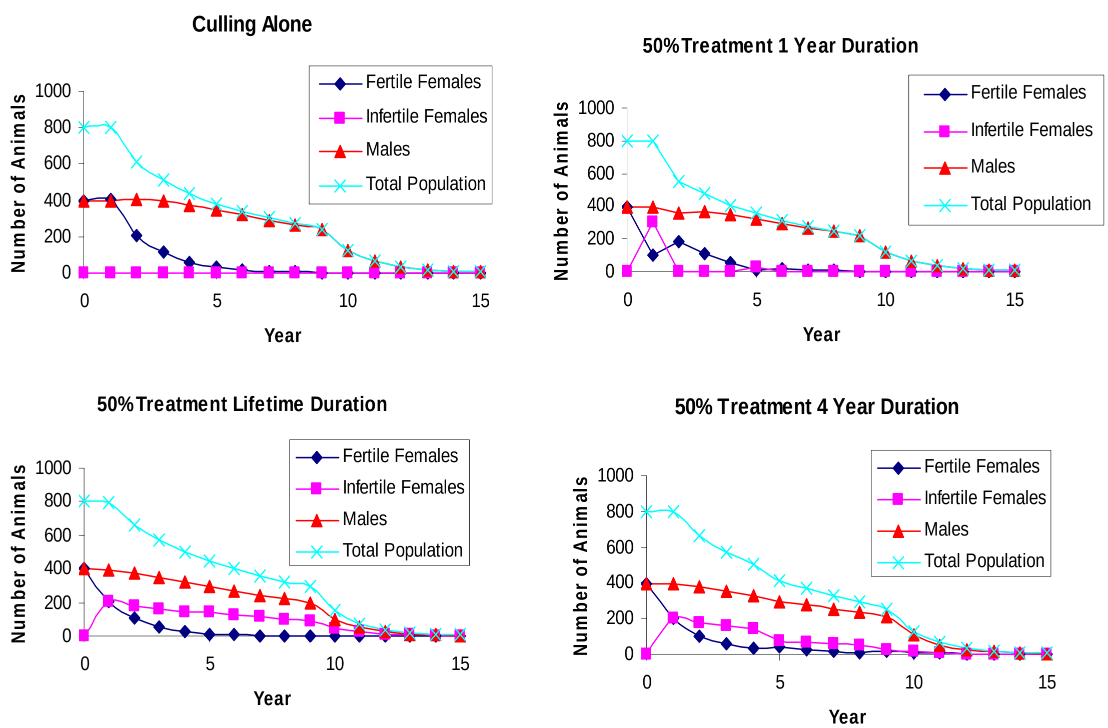


Figure 5. Simulated trajectories of fallow deer populations under four eradication regimes assuming only fertile females were culled before year 10. Shapes of curves for the .25 and .75 treatment levels closely resembled those shown here. Simulations assumed that infertile animals were marked and that only fertile females were culled during years 0-10. Thereafter, culling included males as well as fertile and infertile females.

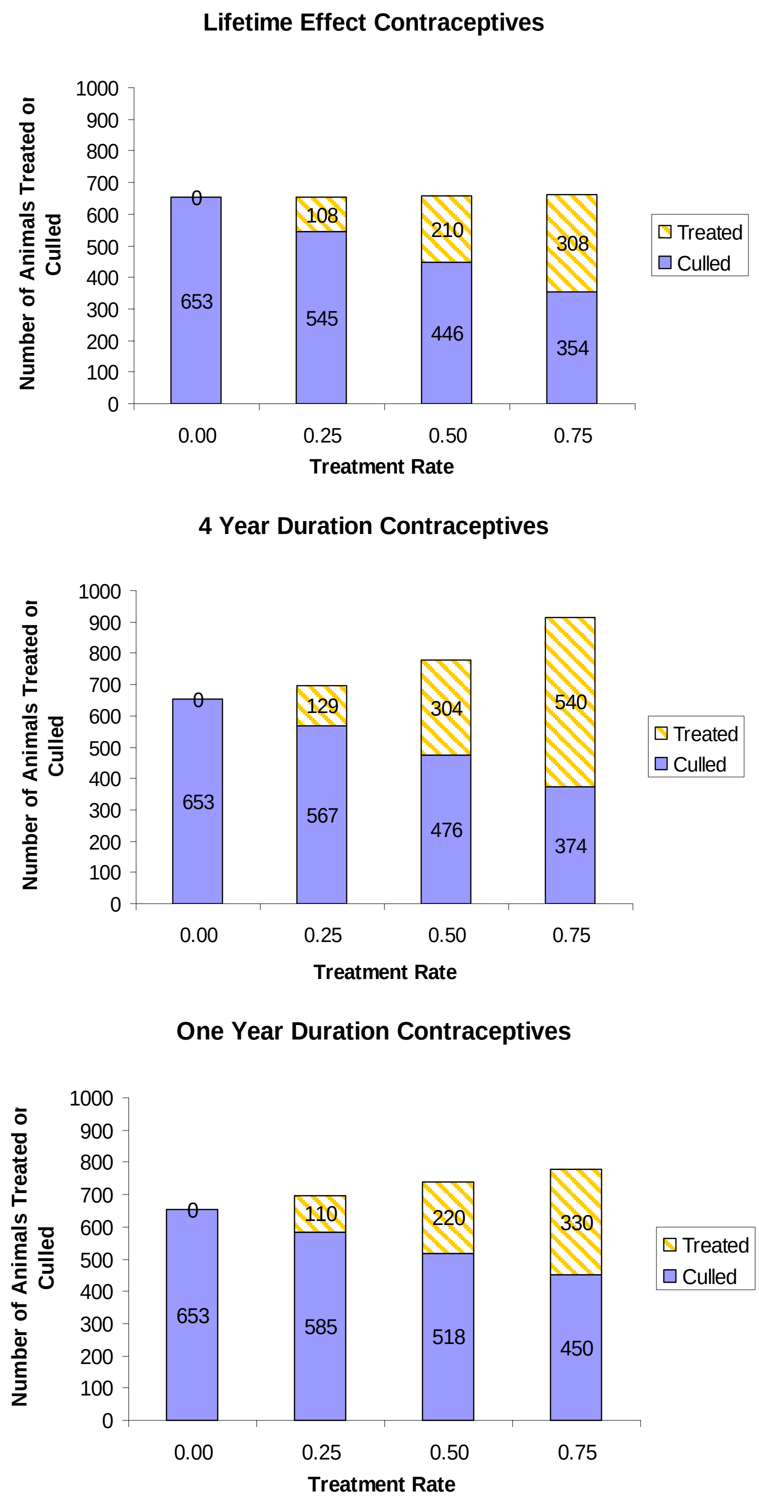


Figure 6. Total number of animals treated and/or culled during simulated 15 year campaign to eradicate fallow deer at Point Reyes National Seashore.

When culling was combined with fertility control, the total number of animals treated + culled was smallest for regimes using lifetime effect contraceptives and largest for regimes using 4 year duration contraceptives (Figure 6). The seeming efficiency of the single year duration contraceptives resulted from effects of culling early in the simulation (Figure 7, Appendix Tables 1-3). High levels of culling were possible in the early years of single year duration simulations because animals became fertile after one year and, hence were vulnerable to culling under the Fertiles Only culling regime. In contrast, animals treated with longer lasting agents would not be culled. The rapid decline in females resulting from culling in the single year duration simulations explains the greater requirement for culling in these simulations and the lower requirement for culling + treatment relative to the 4 year duration simulations (Figure 6, 7).

Virtually all treatment with contraceptives occurred during the first delivery period for the lifetime effect and single year duration contraceptives (Figure 7, Appendix Tables 1-3). This occurred because few fertile females remained the population by year 4 of the simulation, when the next fertility control treatment occurred. In the lifetime duration case, the absence of fertile females in year 4 occurred because the initial treatment and subsequent culling of the untreated portion of the population eliminated fertile females. In the single year duration case, the low numbers of fertile females in year 4 resulted because all females became vulnerable to culling after the first year of the simulation and most were killed before the next scheduled treatment with contraceptives. There were 3 significant treatments with contraceptives for the 4 year duration agents during year 0, 4, and 8. Multiple treatments were required for 4 year duration agents because 1) animals had to be retreated every 4 years to maintain infertility and 2) during the 4 year interval between treatments they were not vulnerable to culling under the Fertiles Only culling regime.

Simulations revealed that attempting to eradicate the population using fertility control alone is futile. Treatment of 75% of the females with single year duration agents every 4 years allowed the population to *increase* slightly. Although longer duration agents reduced the population substantially, they failed to achieve eradication even after 4 treatments applied over 15 years (Table 2). The inability of fertility control alone to reduce the population is easy to understand. Even when 100% of the females are maintained infertile, the maximum rate of decline of the population is no greater than the maximum mortality rate, which, in a long lived species like fallow deer, is quite small, approximately 10% per year.

Table 3. Results of simulation of eradication efforts using fertility control alone. Simulations assumed treatment of 75% of fertile females during years 0, 4, 8, and 12.

	Duration of Contraceptive		
Simulated Response	1 year	4 years	Lifetime
Population during year 15.	884	420	259
Total number of females treated	1318	922	439

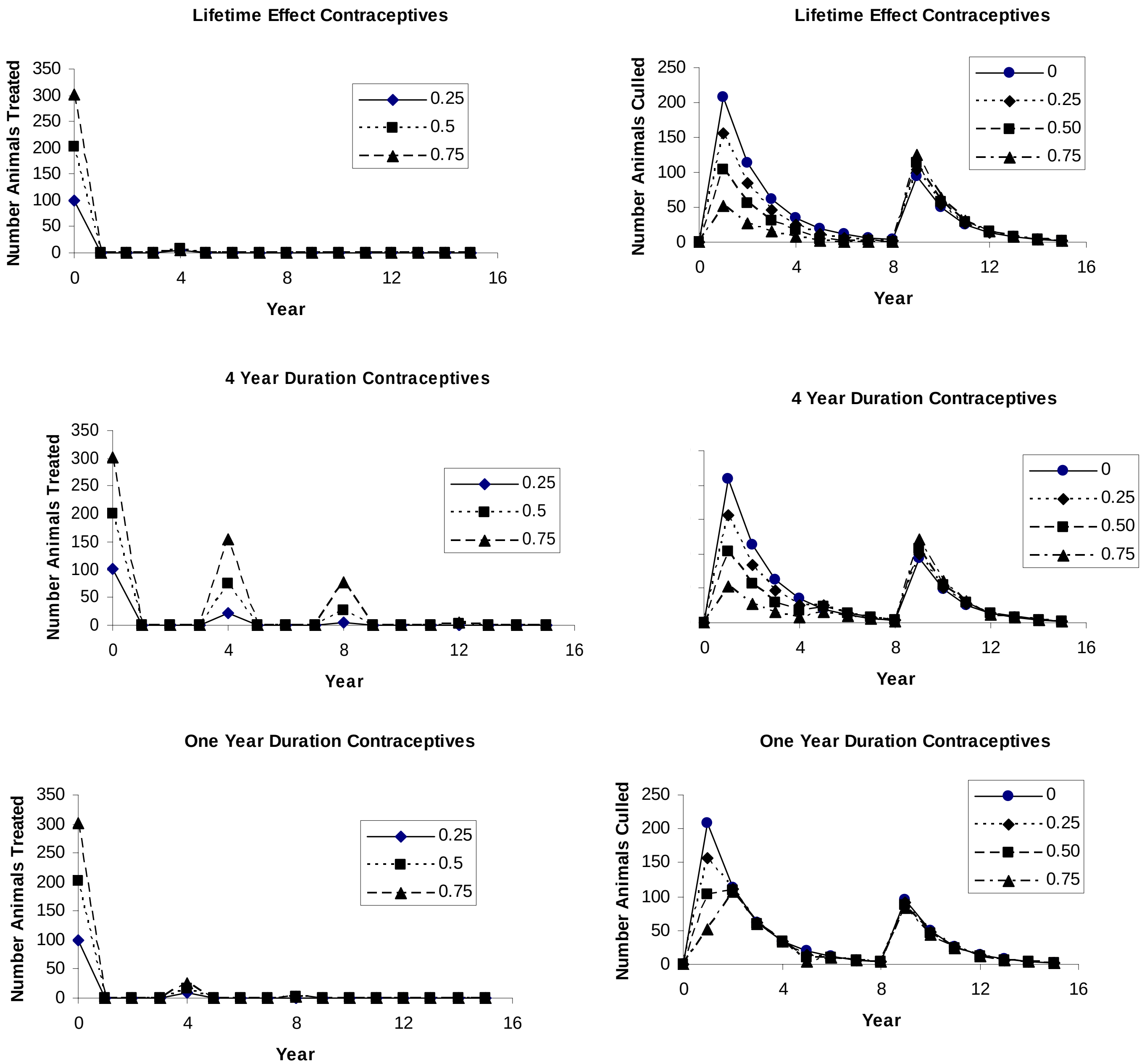


Figure 7. Number of animals annually treated (left column) or culled (right column) during simulated 15 year campaign to eradicate fallow deer at Point Reyes National seashore.

Uncertainty in model predictions was assessed for culling and culling combined with lifetime and 4 year duration contraceptives using Monte Carlo Simulation. This is a technique that uses multiple model runs to estimate the error in model output based on assumptions about the uncertainty in model input. For each model run, input values are chosen randomly for a distribution of potential parameter values. The results of these many runs are accumulated allowing calculation of means and confidence intervals on all model predictions.

Distributions of model parameters were chosen to allow for relatively high levels of uncertainty. (Table 3), thereby providing conservative (broad) confidence intervals on model predictions. Initial conditions for numbers of animals in each age/sex class were estimated by simulating density dependent population growth starting with a population of 20 males and 20 females and allowing the population to grow until it reached a size determined by a random variable drawn from a normal distribution with a mean equal to the current population size and a standard deviation equal to 20% of the mean.

Mean values of model predictions of number of animals treated and culled were calculated as the average of 100 replicate runs. Confidence intervals were estimated from the upper and lower .025 percentiles of the 100 replicates.

Table 4.

Model Parameter	Distribution	Distribution Parameters
Initial N	Normal	Mean = 800, standard deviation = 160
τ	Uniform	lower = .5, upper = 1
s_A	Uniform	lower = .85, upper = .95
s_j	Uniform	lower = .85, upper = .95
m_a	Uniform	lower = .85, upper = .95
m_J	Uniform	lower = .45, upper = .55

Monte Carlo simulations provided reasonable confidence in estimates of the number of animals that would need to be treated or culled to eradicate the population within 15 years assuming the treatment regimes described in the results of deterministic simulations above (Table 5). The means shown in Table 5 do not perfectly match the predictions of the deterministic simulations (Figure 6) because the model is non-linear and stochastic results from non-linear models will not match deterministic results. Moreover the deterministic simulations assumed linear density dependence (i.e., $\tau = 1$) while the Monte Carlo simulations allowed for non-linear density dependence (i.e., $\tau < 1$).

Table 5. Means and 95% confidence intervals for model predictions of the number of animals treated with contraceptives and culled in simulations of a 15 year campaign to eradicate fallow deer from Point Reyes National Seashore.

		Number Treated			Number Culled		
Duration of Contraceptive	Proportion Fertile Females Treated	Mean	95% CI		Mean	95% CI	
4 year	0	0	0	0	677	426	924
	0.25	133	85	176	595	366	848
	0.5	327	219	442	530	324	775
	0.75	570	362	731	409	217	619
Lifetime	0	0	0	0	693	453	988
	0.25	134	89	181	604	349	866
	0.5	306	199	398	486	291	709
	0.75	553	361	795	395	221	709

Effects of Females Only Culling With and Without Fertility Control
Culling fertile and infertile females (but not culling males) substantially reduced any benefits of fertility control. Under this scenario, virtually all reductions in animal numbers resulted from culling. Duration of effects of contraceptives did not modify this result.

Results: Reduce Population to 350 Alternative

Effects of Fertiles Only Culling With and Without Fertility Control
Simulations of culling alone and culling in combination with fertility control indicated that the population could be reduced to 350 animals (including 50 fertile females) within 15 years, but the effort required to achieve this reduction differed among management scenarios. Culling alone required killing 452 animals over the course of the 15 year campaign (Figure 8). Combining culling with fertility control reduced the numbers of animals that would need to be culled, but markedly increased the total number of animals that would need to be treated or culled (Figure 8). The extent of reduction in culling declined with declining duration of the contraceptives; the greatest reductions were achieved by delivering lifetime effect contraceptives. The smallest reductions occurred in simulations of single year duration contraceptives (Figure 8).

When culling was combined with fertility control, the total number of animals treated + culled was smallest for regimes using lifetime effect contraceptives and largest for regimes using 4 year duration contraceptives (Figure 8). The seeming efficiency of the single year duration contraceptives resulted from effects of culling early in the simulation (Figure 9).

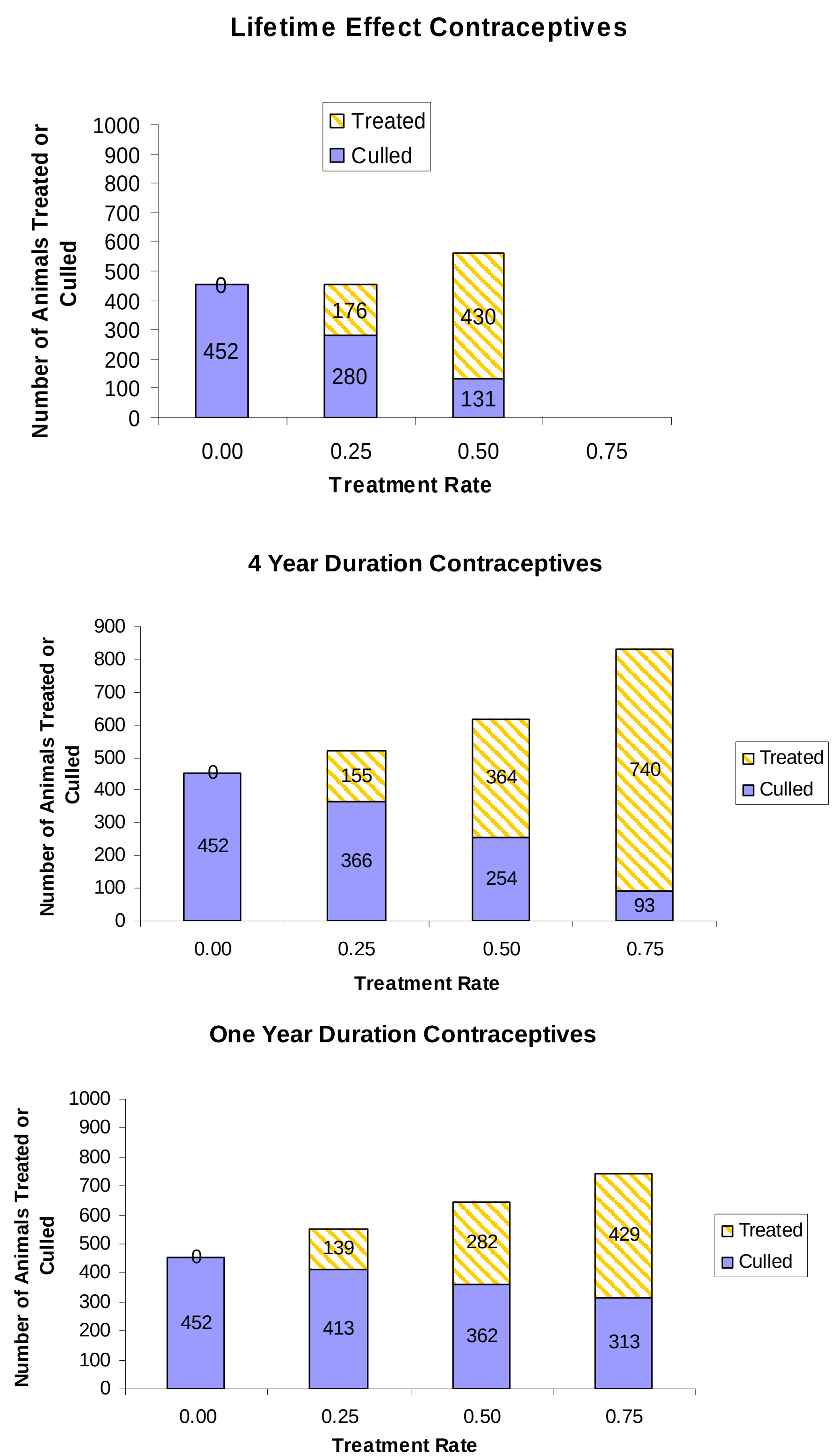


Figure 8. Total number of animals treated and/or culled during simulated 15 year campaign to reduce the fallow deer population at Point Reyes National Seashore to 350 animals in and total fertile females = 50. It was not feasible to treat 75% of the fertile females and maintain 50 fertile females in the population using lifetime effect contraceptives.

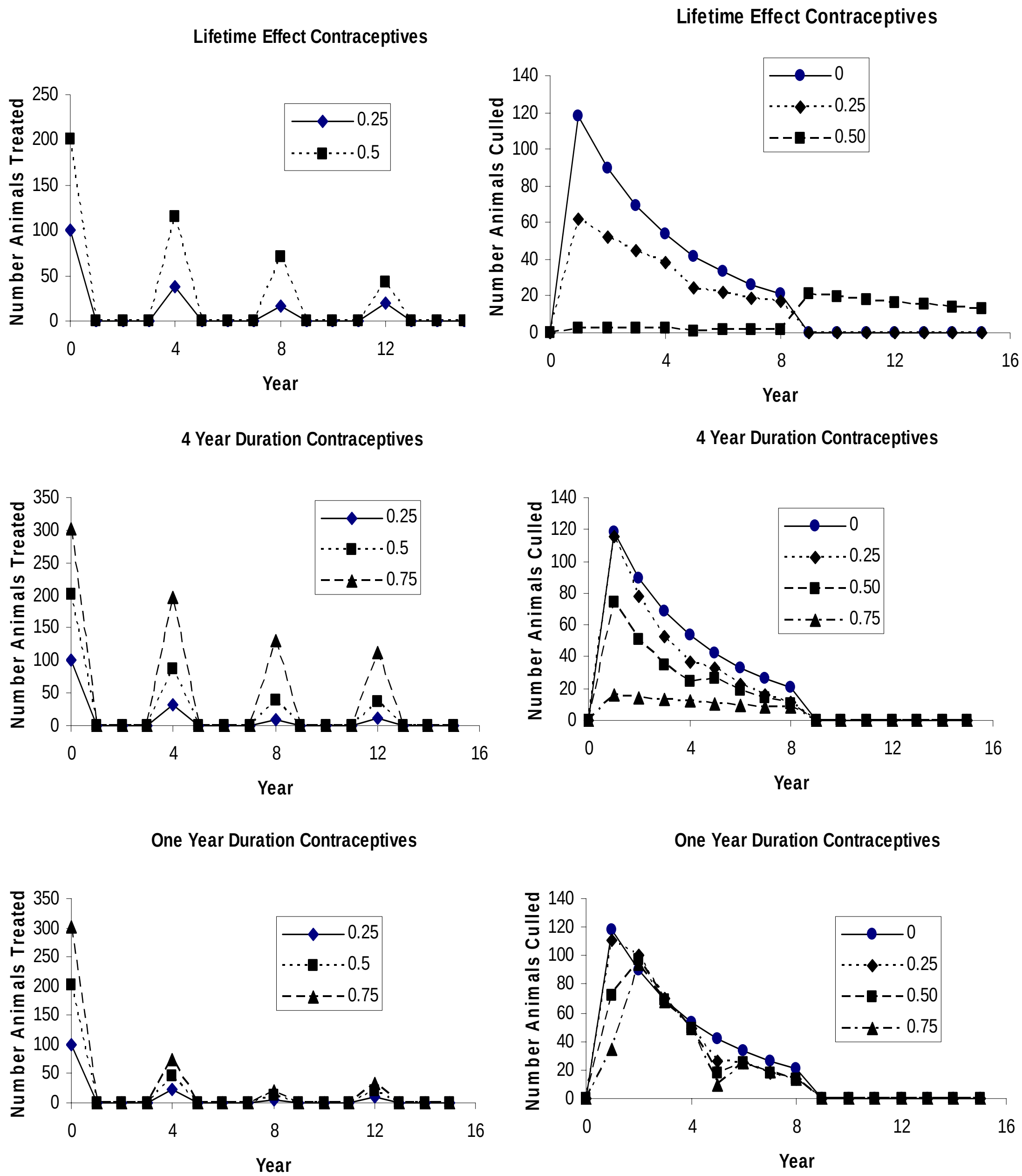


Figure 9. Number of animals annually treated (left column) or culled (right column) at Point Reyes National seashore during simulated 15 year campaign to reduce the fallow deer population to 350 animals, including 50 fertile females. The data in these plots are tabulated in Appendix Tables 4-6.

Discussion

Simulation modeling revealed that a sustained effort could feasibly eradicate fallow deer from Point Reyes National Seashore. It would also be feasible to reduce the population to approximately half the current size. However, the amount of effort required to achieve the two population targets (0 or 350) was not proportionate to the magnitude of the reduction. I estimated that about 650 animals would need to be culled (assuming no fertility control) to eradicate the population, while only 200 fewer would need to be culled to reduce the population to 350 animals.

Although simulations portrayed a 15 year effort, results suggested that eradication in 10 years would be plausible if 50% of the fertile females could be culled annually (Figure 7, 9). Treating animals with contraceptives could substantially reduce the number of animals that would need to be culled if animals could be marked such that only infertile animals were culled in initial phase of reductions. If animals could not be marked, then fertility control had nominal effects on the number of animals culled. However, fertility control did not reduce the total number of animals that would need to be treated and culled, which means that it did not increase the efficiency of culling. The model strongly supported the logical contention that fertility control alone was not a feasible approach to eradication, even when using long duration contraceptives.

There are many uncertainties in the values of parameters used in the model, but error analysis suggested that while these uncertainties might change the quantitative results of simulation, the qualitative conclusions drawn from them remain robust. This means that the absolute number predicted by the model should be viewed with caution, but we can have substantial confidence in the conclusion that sustained efforts at eradication will achieve the desired result. It will be important that such efforts be conducted with careful attention to monitoring the population. Monitoring data should be analyzed with a model like this one, incorporating uncertainty, to guide control efforts. An effort to calibrate estimates of population size with catch per unit effort would likely prove extremely worthwhile over a 10 + year campaign.

Literature Cited

Gogan, P. J. P., R. H. Barrett, W. W. Shook, and T. E. Kucera. 2001. Control of ungulate numbers in a protected area. Wildlife Society Bulletin 29:1075-1088.

Hobbs, N. T., D. C. Bowden, and D. L. Baker. 2000. Effects of fertility control on populations of ungulates: General, stage-structured models. Journal of Wildlife Management 64:473-491.

Appendix Table 1. Simulated number of fallow deer treated with lifetime effect contraceptives and culled during 15 year eradication campaign at Point Reyes National Seashore.

	Treated				Culled			
	Proportion Treated				Proportion Treated			
Year	0	0.25	0.5	0.75	0	0.25	0.5	0.75
0	0	101	201	302	0	0	0	0
1	0	0	0	0	208	156	104	52
2	0	0	0	0	113	84	56	28
3	0	0	0	0	62	46	30	15
4	0	6	8	6	34	25	17	8
5	0	0	0	0	19	11	5	1
6	0	0	0	0	11	6	3	1
7	0	0	0	0	6	3	1	0
8	0	0	0	0	4	2	1	0
9	0	0	0	0	95	104	114	125
10	0	0	0	0	49	53	58	63
11	0	0	0	0	26	27	29	32
12	0	0	0	0	13	14	15	16
13	0	0	0	0	7	7	8	8
14	0	0	0	0	4	4	4	4
15	0	0	0	0	2	2	2	2
All years	0	108	211	309	653	545	446	354

Appendix Table 2. Simulated number of fallow deer treated with 4 year duration contraceptives and culled during 15 year eradication campaign at Point Reyes National Seashore.

	Treated				Culled			
	Proportion Treated				Proportion Treated			
Year	0	0.25	0.5	0.75	0	0.25	0.5	0.75
0	0	101	201	302	0	0	0	0
1	0	0	0	0	208	156	104	52
2	0	0	0	0	113	84	56	28
3	0	0	0	0	62	46	30	15
4	0	23	74	154	34	25	17	8
5	0	0	0	0	19	25	24	16
6	0	0	0	0	11	14	14	9
7	0	0	0	0	6	8	8	5
8	0	5	27	78	4	5	4	3
9	0	0	0	0	95	99	108	121
10	0	0	0	0	49	51	55	61
11	0	0	0	0	26	26	28	31
12	0	1	2	5	13	14	14	12
13	0	0	0	0	7	7	8	8
14	0	0	0	0	4	4	4	4
15	0	0	0	0	2	2	2	2
All years	0	129	304	540	653	567	476	374

Appendix Table 3. Simulated number of fallow deer annually treated with 1 year duration contraceptives and culled during 15 year eradication campaign at Point Reyes National Seashore.

	Treated				Culled			
	Proportion Treated				Proportion Treated			
Year	0	0.25	0.5	0.75	0	0.25	0.5	0.75
0	0	101	201	302	0	0	0	0
1	0	0	0	0	208	156	104	52
2	0	0	0	0	113	111	109	107
3	0	0	0	0	62	61	60	59
4	0	8	17	25	34	34	34	33
5	0	0	0	0	19	14	9	5
6	0	0	0	0	11	10	10	9
7	0	0	0	0	6	6	6	5
8	0	1	2	2	4	3	3	3
9	0	0	0	0	95	91	87	84
10	0	0	0	0	49	47	46	44
11	0	0	0	0	26	25	24	23
12	0	0	0	0	13	13	13	12
13	0	0	0	0	7	7	7	7
14	0	0	0	0	4	4	4	4
15	0	0	0	0	2	2	2	2
All years	0	110	220	330	653	585	518	450

Appendix Table 4. Simulated number of fallow deer treated with lifetime duration contraceptives and culled during 15 year campaign to reduce the population to 350 animals (including 50 fertile females) at Point Reyes National Seashore. It was not feasible to treat 75% of the fertile females and meet the target objectives.

	Treated			Culled		
	Proportion Treated			Proportion Treated		
Year	0	0.25	0.5	0	0.25	0.5
0	0	101	201	0	0	0
1	0	0	0	118	62	2
2	0	0	0	90	52	2
3	0	0	0	69	45	2
4	0	38	115	53	38	2
5	0	0	0	42	25	1
6	0	0	0	33	22	1
7	0	0	0	26	19	1
8	0	17	71	21	17	1
9	0	0	0	0	0	21
10	0	0	0	0	0	19
11	0	0	0	0	0	18
12	0	20	43	0	0	17
13	0	0	0	0	0	15
14	0	0	0	0	0	14
15	0	0	0	0	0	13
All Years	0	176	430	452	280	131

Appendix Table 5. Simulated number of fallow deer treated with 4 year duration contraceptives and culled during 15 year campaign to reduce the population to 350 animals (including 50 fertile females) at Point Reyes National Seashore.

	Treated				Culled			
	Proportion Treated				Proportion Treated			
Year	0	0.25	0.5	0.75	0	0.25	0.5	0.75
0	0	101	201	302	0	0	0	0
1	0	0	0	0	208	156	104	52
2	0	0	0	0	113	84	56	28
3	0	0	0	0	62	46	30	15
4	0	23	74	154	34	25	17	8
5	0	0	0	0	19	25	24	16
6	0	0	0	0	11	14	14	9
7	0	0	0	0	6	8	8	5
8	0	5	27	78	4	5	4	3
9	0	0	0	0	95	99	108	121
10	0	0	0	0	49	51	55	61
11	0	0	0	0	26	26	28	31
12	0	1	2	5	13	14	14	12
13	0	0	0	0	7	7	8	8
14	0	0	0	0	4	4	4	4
15	0	0	0	0	2	2	2	2
All years	0	129	305	540	653	568	476	374

Appendix Table 6. Simulated number of fallow deer treated with 1 year duration contraceptives and culled during 15 year campaign to reduce the population to 350 animals (including 50 fertile females) at Point Reyes National Seashore.

	Treated				Culled			
	Proportion Treated				Proportion Treated			
Year	0	0.25	0.5	0.75	0	0.25	0.5	0.75
0	0	101	201	302	0	0	0	0
1	0	0	0	0	118	111	72	35
2	0	0	0	0	90	100	97	94
3	0	0	0	0	69	70	69	68
4	0	23	47	74	53	50	50	50
5	0	0	0	0	42	27	18	9
6	0	0	0	0	33	25	25	25
7	0	0	0	0	26	18	18	19
8	0	6	13	21	21	13	14	14
9	0	0	0	0	0	0	0	0
10	0	0	0	0	0	0	0	0
11	0	0	0	0	0	0	0	0
12	0	10	20	32	0	0	0	0
13	0	0	0	0	0	0	0	0
14	0	0	0	0	0	0	0	0
15	0	0	0	0	0	0	0	0
All years	0	139	282	429	452	413	362	313