22 Jul 2020
Vickie L. DeNicola
White Buffalo Incorporated
26 Davison Road
Moodus, CT 06469
Ph: (818) 261-1319
vickie.denicola@whitebuffaloinc.org

Surgical Sterilization as a Management Technique in Suburban Deer Populations

ANTHONY J. DENICOLA, *White Buffalo Incorporated, 26 Davison Road, Moodus, CT 06469, USA*

VICKIE L. DENICOLA,[1] *White Buffalo Incorporated, 26 Davison Road, Moodus, CT 06469, USA*

ABSTRACT Overabundant suburban deer (*Odocoileus* spp.) are a source of human-wildlife conflict in many communities throughout the United States. Deer-vehicle collisions, tick-borne pathogens, impacts on local vegetation, and other negative interactions are the typical reasons cited for initiating a deer management program. Social attitudes, legal constraints, and perceived safety concerns lead many communities to examine nonlethal management options. Surgical sterilization is currently the only nonlethal method available to permanently sterilize females with a single treatment. There are limited data demonstrating methods and outcomes in management programs that sterilize a high percentage (>90%) of the population, particularly in terms of the impact of immigration on non-isolated populations. We present data from 6 surgical sterilization sites with open populations (not fully enclosed or island environments) in California, Maryland, Michigan, New York, Ohio, and Virginia, USA. From 2012 to 2020, we sterilized 493 deer primarily via ovariectomy. Annual or periodic population estimates were conducted using camera surveys, road-based distance sampling, and intensive field observations to assess population

[1] *Email:* vickie.denicola@whitebuffaloinc.org

trends. Initial populations ranged from 6 - 63 deer/km^2. For all 6 sites combined, we noted an average reduction in deer abundance of approximately 25% from Year 1 to Year 2. Four years after first treatment at sites managed with only surgical sterilization, we noted an average total population reduction of 45%. These projects demonstrate that significant reductions in local deer densities using high percentage surgical sterilization programs can be achieved in non-insular locations.

KEY WORDS deer management, fertility control, human-wildlife conflicts, nonlethal, population management, *Odocoileus* spp.

In many urban and suburban situations, lethal management techniques such as controlled hunting and sharpshooting are not feasible or practical because of legal, social, public safety or economic considerations (Williams et al. 2013, Kilpatrick et al. 2014). As a result, a variety of non-lethal management techniques such as trap and relocation or fertility control have been explored (DeNicola et al. 2000). Fertility control options have been prioritized because trap and relocation has been demonstrated to be stressful and result in unacceptably high post-release mortality (Beringer et al. 2002).

There has been extensive research conducted on injectable or implantable wildlife fertility control agents for nearly 5 decades, with numerous studies conducted in the 1970s and 1980s (Harder and Peterle 1974, Bell and Peterle 1975, Matschke 1977, Kirkpatrick and Turner 1985, Plotka and Seal 1989). Recent research has transitioned focus to vaccines and surgical sterilization as the most promising approaches (Patten et al. 2007). Given the scope of research, there has been relatively little improvement in the function of vaccines tested in the late-1980s on horses (Liu et al. 1989, Kirkpatrick et al. 1990) or deer in the 1990s (Turner et al. 1992, McShea et al. 1997, Miller et al. 1997, Miller et al. 2000). For long-lived species, at least one booster is

necessary to predictably maintain >90% effectiveness for >2 years, even for declared “one-shot” vaccines (Gionfriddo et al. 2011, Rutberg et al. 2013a, Roelle et al. 2017).

Wildlife professionals have discussed the potential of fertility control as a wildlife management technique for as long as efficacy trials have been conducted (McCullough 1987, Bomford 1992, Warren 1995, Garrott 1995, Miller et al. 1998). However, research to date has described the limitations of fertility control versus its potential to effectively manage deer overabundance in open environments. Most research has focused on delivery methods and treatment efficacy, with very few assessments of management outcomes, though several studies have concluded that in order for fertility control to be successful, its use must be limited to small, insular or fenced areas (Seagle and Close 1996, Merrill et al. 2006, Boulanger et al. 2012, Boulanger and Curtis 2016). These conclusions were founded on a few population-level field studies conducted at the National Institute of Standards and Technology, Gaithersburg, Maryland, USA (Rutberg and Naugle 2008; porous fenced property – 27% reduction over 5 years), Fire Island National Seashore, Patchogue, New York, USA (Naugle et al. 2002; 58% reduction over 10 years), and Fripp Island, South Carolina, USA (Rutberg et al. 2013b), as well as modeling efforts (Seagle and Close 1996, Merrill et al. 2006). The only modeling effort that projected a positive outcome using surgical sterilization (i.e., reduced local population) assessed Cumberland Island, Georgia, USA (Boone and Wiegert 1994).

Conclusions on the potential management benefits of fertility control have also been based on poorly designed research, faulty assumptions of what percentage of a deer population can be captured, and exaggerated immigration impacts. For example, Boulanger and Curtis (2016) selected a surgical method (tubal ligation) that caused extended estrus periods and concluded that surgical sterilization would not work in open environments without a lethal component. In their

study, adult female and fawn numbers declined significantly, reflecting an effective program, but male abundance increased 9-fold, preventing an overall population decline. Given the sterilization method used, males were potentially attracted to females that exhibited repeated estrous cycles. Antlered males also likely sought refuge in the non-hunted study site given the earn-a-buck hunting program occurring around the site (Williams et al. 2008, Boulanger et al. 2014). As a result, it was concluded that sterilization would not reduce deer abundance in open populations. In contrast, MacLean et al. (2006) found limited immigration and no population increase due to sterilization via tubal ligation (no male increase) in an open suburban environment without proximate hunting.

The first assessment of surgical sterilization on deer was conducted by Frank and Sajdak (1993) and additional research on surgical methods occurred in the 2000s (MacLean et al. 2006, Boulanger et al. 2012). These efforts were initiated in recognition that immunocontraceptive vaccines were limited in their effectiveness/longevity and an alternative was needed in areas where treating the same animal more than once was too difficult or costly. As a result, we decided to conduct additional fertility control research, using surgical sterilization via ovariectomy, to reduce population abundances while eliminating breeding behavior associated with tubal ligations. Our interest was to identify a method that could be used as a surrogate for the “future ideal infertility treatment” to document population-level impacts on white-tailed deer (*Odocoileus virginianus*). Our research focused on the potential of surgical sterilization of female deer as a management tool in open suburban environments and semi-enclosed developed areas. Porter et al. (2004) demonstrated strong philopatry of female white-tailed deer, and we have observed similar behavior over the past 25 years of implementing deer management programs (A. J. DeNicola, unpublished data). These findings supported our rationale for testing sterilization in open

environments, given limited immigration risks. We selected research locations based on fundamentals outlined by Garrott (1995) and Rudolph et al. (2000) that noted the need for extensive access and approachable deer. McCullough (1987) also emphasized that suitable sites be selected for applying fertility control treatments. Most researchers have concluded that 60-80% or higher (Grund 2011) of a deer population needs to be rendered infertile to stabilize or begin to reduce a local population (McCullough 1987, Hone 1992, Garrott 1995, Boulanger et al. 2012). Our primary objective was to capture and permanently sterilize >95% of females in each designated study area and assess effort, impact, and immigration rates as populations declined.

STUDY AREAS

We applied surgical sterilization treatments to free-ranging deer on 6 study sites. White-tailed deer were the target species at every site except The Villages Golf and Country Club (VGCC) where we captured and treated black-tailed deer (*Odocoileus hemionus columbianus*). Deer capture efforts were typically conducted during the locally prevailing winter seasons from 2012-2020 to minimize stress on deer and maximize baiting success. Each study site initiated surgical sterilization applied research projects to address increasing deer-vehicle collisions, landscape damage, forest diversity impacts, or tick-borne infection concerns. Decision-makers at each location opted to use a non-lethal approach because of either social or legal constraints. Two communities opted to incorporate culling because of disparity in development patterns or a change in legal restrictions in discharge setbacks.

All of our study sites were typified by a mixture of developed urban or suburban landscapes with intermingled wetlands or other small to moderate open spaces. Except for the National Institutes of Health (NIH) campus, they were primarily single-family residential communities with property sizes ranging from 0.4 – 2.0 ha with some larger private properties

interspersed (e.g., golf courses). Only the NIH campus and the VGCC community had security fencing. Neither fence prevented deer from entering or exiting with documented emigration from both locations and annual immigration at NIH. The other study sites were not isolated from the surrounding areas that contained resident deer populations. Hunting was not permitted in any of the study sites because of safety concerns associated with high-density development and significant human activity. Regional differences in climate among our various study sites affected the local natural plant communities.

Ann Arbor, Michigan, USA (N42.2709, W83.7263; AA) is in Washtenaw County and consists of 74.5 km^2 of total land area. There were 121,477 people (47,524 households) as of the 2017 census, with most of its land area covered by single-family homes surrounded by wooded corridors. This research project focused on the potential benefits of using combined deer management methods; sharpshooting was utilized in larger open spaces, whereas sterilization efforts were concentrated in the more densely developed neighborhoods. We established 3 surgical sterilization study areas throughout the community, but only focused on the largest and most isolated from undeveloped areas in this analysis (Fig. 1). The focal study area was 4.3 km^2 and sharpshooting occurred adjacent to the northern and eastern borders. Sharpshooting was initiated immediately after the surgical sterilization phase. Sterilized deer were not culled during sharpshooting operations. The City's management goal was to reduce deer densities to the point where 75% of surveyed residents reported satisfaction with the deer abundance.

The Clifton neighborhood of Cincinnati, Ohio, USA (N39.1531, W84.5248; CLIF), is located in the north-central section of the city and consists of ~4.9 km^2 of total land area. The 2.4 km^2 study site contains Mt. Storm, Rawson Woods, and Edgewood Grove parks, as well as the surrounding neighborhoods. The parks are generally undeveloped and include steep wooded

hillsides and some mowed open space. Because deer were not limited to the parks under consideration, we delineated the study as depicted in Fig. 2. Deer densities had reached a level that was considered incompatible with the Cincinnati Park Board's goal of a healthy park ecosystem.

Fairfax City, Virginia, USA (N38.8462, W77.3064; FC) is located in the western suburbs of Washington, D.C. and is ~16.5 km^2 (Fig. 3). There were 24,097 people and 8,843 households as of the 2017 census. The use of bait for capture or camera survey population estimates was not permitted during the first year. After it was demonstrated that baiting would be instrumental to the success of the project and improved accuracy of camera surveys, Virginia Department of Game and Inland Fisheries (VDGIF) amended the research permit allowing the use of bait.

The NIH site (N38.9992, W77.1025) is an office park complex located in Bethesda, Maryland, USA (Fig. 4). The study area was 1.2 km^2 and contains small natural and landscaped areas interspersed dense commercial development. Landscape damage and deer-vehicle collisions were of concern.

The Village of Cayuga Heights, New York, USA (N42.4687, W76.4856; VCH) is located adjacent to and contiguous with the City of Ithaca and contains 4.6 km^2 (Fig. 5). At the start of this study, New York State law prevented discharge of a weapon such as a bow, muzzleloader, or firearm within 152 m of an occupied dwelling without owner permission. As a result, and given local opposition to a lethal management program, there were no legal locations to cull deer in VCH. Therefore, elected officials voted to implement a surgical sterilization initiative starting in 2012 given the abundance of deer and associated conflicts. In 2014 the law changed reducing archery discharge to 76 m which permitted a cull conducted from 2015-2017. The community leadership decided to incorporate archery culling to accelerate the population decline. The State of

New York then prohibited baiting within 91 m of a public road in 2017 and only 2 properties remained legal given the high road density. As a result, VCH decided to transition to a program of remote immobilization followed by euthanasia from 2018-2019 to obtain even lower deer densities. We include data and discussion on subsequent culling activities to allow for insights on immigration as the population declined.

The VGCC is in San Jose, California, USA (N37.2878, W121.7466) and is a 2.7 km^2 private golf community with 2,536 homes and an 18-hole golf course (Fig. 6). Landscape damage and replacement costs exceeded $250,000 annually because of deer impacts (B. Barncord, personal comm.) and the community elected to execute a non-lethal management program as a result.

METHODS

All capture and surgical procedures were conducted by wildlife veterinarians or employees of White Buffalo, Inc. who were trained by a wildlife veterinarian in humane capture and chemical restraint methods. Capture and handling was conducted in accordance with Michigan Department of Natural Resources Scientific Collectors Permit #1600, Ohio Department of Natural Resources scientific collection permit #18-48, VDGIF Scientific Collection Permit #058581, Maryland Department of Natural Resources Deer Cooperator Permit 55832-NIH-2014-2017 and NIH Office of Research Services Animal Study Proposal Animal Care and Use Committee #ORS-54, New York State Department of Environmental Conservation License to Collect and Possess #2558, and California Department of Fish and Wildlife Scientific Collection Permit #SC-012522.

Deer Capture

Female white-tailed deer of all age classes were immobilized using projectors with 2-ml transmitter darts (Pneu-Dart, Inc., Williamsport, PA, USA) to administer tiletamine/zolazepam

(4.4 mg/kg) and xylazine hydrochloride (2.2 mg/kg; Kilpatrick et al. 1997). We approached deer in a vehicle on public roadways and private roadways/properties where permission was granted. In some locations, a police officer accompanied each capture professional during mobile darting (i.e., AA, FC, and VCH; Evans et al. 2016). We also darted deer over bait (i.e., whole-kernel corn) in the late afternoon and early evening where state regulations permitted. Once a dart was deployed and 10 minutes had elapsed, deer were located via radio-telemetry if not visibly recumbent. In VCH, we also captured deer with drop nets during the first year (December 2012). We chemically immobilized adult deer under drop nets with an intramuscular injection of 400 mg ketamine hydrochloride (HCl) and 150 mg xylazine HCl <2 minutes after capture. Fawns were administered 300 mg ketamine HCl and 100 mg xylazine HCl. All captured deer were fitted with ear tags for individual identification (Destron Fearing Duflex X-Large Cattle Tag, Dallas, TX, USA) and the backplate of each labeled “Call Before Consumption” and a phone number. We followed deer handling, tagging, and transport methods summarized by Evans et al. (2016). In addition, some captured females were fitted with VHF radio-collars containing 8-hour mortality sensors to facilitate future capture efforts and assess survival rates (Model 2220, Advanced Telemetry Systems, Isanti, MN, USA).

Surgical Sterilization Procedure

We followed surgical procedures summarized in Evans et al. (2016). Initially, we conducted bilateral ovariectomies using a combination of clamping, electrocautery, and excision for removal and coagulation to prevent hemorrhage. We transitioned to a vessel sealer in fall 2016 to expedite the procedure and minimize risks associated with post-surgical bleeding (Valleylab LigaSure, Medtronic, Minneapolis, MN, USA). We conducted fallopian tubal ligectomies (n = 26) only

when deemed necessary by veterinarians (e.g., extensive adhesions that complicated the extraction of the ovaries, late gestation).

We also followed post-surgical release and monitoring procedures documented in Evans et al. (2016). The one exception was that we relocated 30 deer outside the fence at VGCC (on adjacent VGCC-owned property) to assess whether these deer would return or remain outside and increase the rate of population decline. To differentiate these relocated deer from the rest of the herd, they received one yellow and one white extra-large ear tag.

Effort

We recorded data to assess the person-hours required for the capture process and sterilization surgery. Capture, handling, and deer transport to and from surgical locations were conducted by biologists and volunteers. For each study site, we divided the number of person-hours devoted for capture and transport by the number of deer captured to derive an estimate of effort per deer. The surgical team typically consisted of 2 people (i.e., trained and licensed veterinarians and technicians). We recorded surgery effort each capture night from the time the first deer was darted until the last deer was released; these total person-hours were then divided by the number of deer sterilized to derive an estimate of surgical effort per deer.

Population Estimates

Population monitoring was conducted before, but typically after sterilization efforts using camera data from baited locations, driving distance transects, and intensive field observations. We noted immigrants, antlered males, fawns, and both tagged and untagged females.

Camera surveys - At 4 study sites (AA, CLIF, FC, VCH), we conducted baited camera surveys using tagged deer to estimate deer abundance (Jacobson et al. 1997, Koerth et al. 1997, Curtis et al. 2009). We used game cameras (D-80 White Flash Trail Cameras, Moultrie,

Alabaster, AL, USA) set on motion activated single shot with a 5-minute delay to optimize capture rates. Camera coverage of ~1/0.61 km^2 was used with one camera placed in each block. Sites were pre-baited for at least 7 days. Each camera was placed 5-6 m from the center of bait (e.g. 20-25 kg whole kernel corn), elevated 0.6 m, and oriented north. Cameras were typically retrieved once $\geq$300 photos were obtained from each baited location. There were some situations where cameras were retrieved with <300 photos (i.e., due to low deer activity), but cameras were left in the field for ~2 weeks. In the first year of FC, baiting was not permitted. To conduct this unbaited camera survey, we divided FC into 12 quadrants, 1 camera was allocated to each quadrant. Public property in each quadrant was scouted for heavily traveled deer trails and pinch points through which deer were forced to pass.

Each image was carefully studied, all legible ear tag numbers were documented, and images of insufficient quality were excluded (e.g., lens flares, poor image quality). We recorded the total number of deer, tagged and untagged individuals, unidentifiable tagged deer, identifiable and unidentifiable antlered males, and untagged fawns in each photo. From these photographic data, we documented the total number of observations of each identifiable, tagged deer, the total number of untagged deer, and the total number of tagged deer known to be alive in the population during the survey. If a tagged deer was not observed on camera or directly for 2 years, we eliminated it from the population projections and noted it as not present.

We entered the number of tagged, untagged, and tagged but unidentifiable observations from each photograph into Program NOREMARK (White 1996). Our tagged individuals were adult females, with occasional female fawns and incidental male fawns. We used the Bowden estimator that assumes sightability is not influenced by tag status, many animals are sighted repeatedly, and the population is closed (Bowden 1993, Bowden and Kufel 1995). The resulting

population estimate and confidence intervals for this method were for adult females or antlerless deer. We used Jacobson's (1997) buck:doe ratios (BDR method) to estimate the number of individual antlered males. We used camera data to determine the ratio of tagged to untagged adult females photographed to estimate the total number of adult females and fawns, assuming equal sightability (Eberhardt 1969). We then added the number of individual antlered males identified using the BDR method to the photographic ratio estimates of adult females and fawns to obtain a population estimate, noted as Lincoln-Peterson estimator (LPE) method. Finally, we used a population reconstruction approach to develop a population estimate. We estimated the number of adult females and fawns, given the high percentage capture status, intensive field observations (e.g., capture observations, bait site data, population estimate data), and known mortality/dispersal data. This estimate method also included the number of antlered males found using the BDR method and any field observations. We then used these three estimates (e.g., NOREMARK, LPE, and population reconstruction) to derive a final estimate. Field observations and photographic data also were used to determine the percentage of females sterilized after each annual capture session, antlerless immigration, and the fawn:adult female ratio.

In VCH, independent camera surveys and population estimates using NOREMARK were conducted from 2013-2016, after capture efforts were completed (2013-2014), and prior to culling efforts (2015-2017; Curtis et al. 2013; 2014, Curtis and Ashdown 2015; 2016; 2017). In 2018, population reconstruction was used to estimate the population pre/post culling (i.e., incorporate harvest data and additional camera data and field observation during the culling efforts).

Distance sampling - In VGCC, a non-overlapping 14.6-km driving transect was established and surveyed 3-5 times, either during the morning or evening, from 7-8 September 2011 and 9-11 October 2012. Surveys were conducted starting 2 hours before sunset and 1 hour

after sunrise. While driving 15-20 kph in a golf cart, spotters searched their respective side of the road. Upon sighting deer, we recorded the number in each social group, age, and sex of the individuals, whether deer were tagged or untagged, and the perpendicular distance to center of the group. These data were entered into the software program Distance (Version 6.0; Thomas et al. 2010) to determine a population estimate and confidence interval.

Complete Census - In VGCC beginning in fall 2014, 10 - 12 volunteers were each assigned to separate neighborhoods and recorded observations of every deer they encountered, including tag numbers and antler patterns. We tallied the number and age class of individual animals observed as an estimate of the population because the deer were very visible. Observers were active for 2-3 hours before sunset for 5 days.

Given the small area and relatively open landscape at NIH, we walked the available habitat areas 2-3 hours before sunset and recorded tagged individuals, males based on antler configuration, and untagged antlerless animals, noting any fawns. We walked the facility twice during each estimate and drove intensively over the 2-day field operation. The total of individual animals observed was used as a census of the population given the deer were highly visible.

RESULTS

Capture and Surgical Sterilization

Deer capture and sterilization activities were conducted between August and March from 2012-2020 (Table 1). We handled 570 deer, including incidental male captures, recaptures, capture related mortalities, and animals euthanized due to pre-existing conditions. During one field session at VCH, we captured 29 incidental males under the drop net. Otherwise, incidental males accounted for 32 captures across all other sites and sessions. We performed 493 successful surgical sterilization procedures at the 6 study sites and experienced 6 failed surgeries (~1%;

Table 1). One deer with a failed surgery in VCH had an ovary remaining that was extracted upon recapture. Veterinarians were unable to locate the uterus in one deer in AA (e.g., expected previous prolapse) and the individual was later recaptured and successfully sterilized. We documented four surgical failures in CLIF due to a deficient surgical method that left remnant ovarian tissue (i.e., the entire ovarian capsule was not removed allowing for regrowth of tissue). When surgeries failed, single fawns were recruited, and in all cases, animals were recaptured and retreated. At CLIF, 2 females were recaptured to confirm lactational status (e.g., check for failed surgery), and at VCH, 2 treated females were incidentally recaptured with the drop net. Overall, 74% (range: 35-92%) of the females were treated in the first year, and 87% (range: 65-100%) in the first two years of each project.

Mortality Rate

In AA, we did not experience any mortalities during the capture and sterilization process over 3 years while handling 67 total deer. We experienced 3 mortalities during the capture and sterilization process over 5 years in CLIF; a 3% mortality rate. Two were recorded post-surgery during the recovery process and 1 female was injured during capture. We experienced 1 mortality during the capture process over 5 years in FC; a 2% mortality rate. We experienced 4 mortalities during the capture and sterilization process over 5 years at NIH; a 9% mortality rate. One female was injured during the capture process and 3 females died post-surgery. During 3 field sessions at VCH, we experienced 3 capture and sterilization related mortalities, and 2 deer were euthanized because of pre-existing injuries; a 2% mortality rate due to handling. During capture efforts in VGCC, we experienced 4 post-release mortalities. Cause of death was determined through necropsies (California Animal Health & Food Safety Laboratory System, Davis, CA, USA) and we recognized a 3% mortality rate. One incidentally captured male likely died due to acidosis

from grain placed out by residents. One treated female was killed by coyotes ~400 m from the release location, and 2 females died from internal bleeding caused by inadequate clotting at the ovarian removal site. One of the females that died due to internal bleeding had numerous severe pre-existing conditions, likely predisposing her to post-surgical complications.

Surgical and Capture Effort

Surgical and capture effort for each project location is summarized in Table 2. Local volunteers participated at 4 locations (e.g. AA, CLIF, FC, and NIH) and, as appropriate, volunteers handled tasks such as pre-baiting, site preparations, transportation, and surgery (when qualified). Accounting for volunteer hours and our time spent training and providing oversight to volunteers was difficult, so we could not accurately account for these times. We used effort per deer captured versus total person-hours that included pre-capture preparations. In general, annual increases in capture effort per deer occurred as fewer deer were available in each study area.

Population Estimates

For all 6 sites combined, we noted an average reduction in deer abundance of approximately 25% from Year 1 to Year 2. Four years after first treatment at sites managed with only surgical sterilization (CLIF, FC, NIH, VGCC), we noted an average total population reduction of 45%. Site specific details are as follows:

Ann Arbor— From 2017 to 2020, population estimates ranged from 94 (21.9 deer/km^2) in 2017 to 50 (11.6 deer/km^2) in 2020 (Table 3), representing a 47% decline. The percentage of adult females sterilized ranged from 90% in 2017 to 97% in 2018, with 88% of adult females sterilized in 2020. The initial fawn to adult female ratio of 1.1:1 in 2017 declined to 0.1:1 by 2018 and remained at 0.1:1 in 2020. The antlered male population ranged from 6 in 2017 to 13 in 2018. The

antlered male population was stable since 2018 at ~11-13 antlered males. We noted 4 immigrant adult females between 2017 and 2020.

Clifton—From 2015 to 2020, population estimates ranged from 99 (41.3 deer/km^2) in 2015 to 72 (29.9 deer/km^2) in 2020, representing a 28% decline. The percentage of adult females sterilized ranged from 86% in 2015 to 98% in 2020. The initial fawn to adult female ratio of 0.6:1 in 2015 declined to 0.1:1 in 2017 and remained at 0.1:1 in both 2018 and 2020. The antlered male population ranged from 32 in 2015 to 16 in 2020. The initial decline was largely made up of younger males (e.g., male fawns, yearlings). We noted 5 immigrant adult females between 2015 and 2020.

Fairfax City—Population estimates in FC ranged from 91 (5.5 deer/km^2) in 2014 to 40 (2.4 deer/km^2) in 2018, representing a 56% decline. The percentage of adult females sterilized ranged from 31% in 2014 to 93% in 2015. In 2018, the percentage sterilized was 91%. The fawn to adult female ratio ranged from 1.3:1 in 2014 to 0.1:1 in 2016. In 2018, the final estimate was 0.2:1. The antlered male population ranged from 6 in 2014 to 16 in 2015 and was stable between 2015 - 2018 ranging from 13-16 individuals. We noted one immigrant adult female between 2014 and 2018.

National Institutes of Health—From 2014 to 2019, population estimates ranged from 47 (39.2 deer/km^2) 2014 to 14 (11.7 deer/km^2) in 2019, representing a 70% decline. The percentage of adult females sterilized was 100% during each annual estimate from 2014 to 2018, and due to one immigrant in 2019, the percentage dropped to 89%. The initial fawn to adult female ratio of 1.4:1 in 2014 declined to 0.1:1 in 2015 and remained at 0.1:1 or 0.0:1 in subsequent years. All fawns identified after 2014 were associated with adult females that had immigrated. The antlered male population ranged from 11 in 2014 to 4 in 2019. The initial decline was largely made up of

younger males (e.g., male fawns, yearlings). We noted 20 immigrant adult females between 2014 and 2019. We were able to sterilize these typically transient females as they came into the study area.

Village of Cayuga Heights— From 2013 to 2015, population estimates ranged from 225 (48.9 deer/km^2) to 137 (29.8 deer/km^2). This represented a 39% decline from 2013 to 2015 with sterilization alone. After 2015, population estimates were refined post-cull and ranged from 68 (14.8 deer/km^2) in 2016 to 9 (2.0 deer/km^2). This represented a 96% decline from 2013 to 2018, using surgical sterilization and culling. The percentage of adult females sterilized ranged from 99% in 2013 to 71% in 2018. The fawn to adult female ratio ranged from 0.6:1 in 2013 to 0.02:1 in 2016. The ratio was 0.3:1 in 2018. The antlered male population was not estimated. We noted 52 adult female immigrants between 2013 and 2018.

From 6-14 March 2015, the archery cull removed 48 deer from the community (Table 4). In 2016, the archery cull removed 24 deer from the community. We captured and sterilized 5 adult females after the archery cull. All females captured after the culling phase were within 100 m of the municipal border, indicating that a majority of their home ranges were outside of VCH, and they were not detected during the camera surveys or while cameras were active during archery culling activities. In 2017, 13 deer were removed during the archery cull. In Year 6, dart and euthanasia efforts removed 45 deer.

Villages Golf and Country Club—From 2010 to 2019, population estimates ranged from 169 (95% CI: 105-223) (62.6 deer/km^2) in 2012 to 46 (17.0 deer/km^2) in 2019. This change represented a 73% decline from 2012 to 2019. Our initial population estimate in 2010 noted 80 deer (95% CI: 48-95) and a 1:1 adult female to fawn ratio. Treatment efforts began in early 2013. During February 2013 capture efforts, 30 deer (4 male fawns and 26 adult females) were relocated

outside the fenced portion of the property, of which 3 returned prior to the conclusion of capture efforts. In October 2013, 13 additional relocated female deer had returned to the fenced property. The percentage of adult females sterilized was at 100% from 2013-2018 and declined to 98% in 2019 due to one immigrant adult female. The initial fawn to adult female ratio of ~1:1 noted prior to treatment between 2010-2013 declined to 0.0:1 in 2014 and remained there until 2020. The one immigrant female with a fawn brought the ratio to 0.02:1. The antlered male population ranged from 40 in 2013 to 6 in 2018/2019. The initial decline was largely made up of younger males (e.g., yearlings, male fawns). We noted 3 immigrant adult females between 2013 and 2019.

Immigration

We detected 85 immigrants across all study sites between 2012-2020, with 52 immigrant individuals detected at VCH. Immigration estimates are summarized in Table 3.

DISCUSSION

Non-surgical wildlife infertility methods have stagnated in terms of improved efficacy and longevity, and surgical sterilization has been shown to be more cost-effective with longer-term efficacy under some circumstances (Evans et al. 2016). Present vaccine treatment options have changed minimally since early summaries of the status of fertility control technology (Bomford 1992, Warren 1995, Miller et al. 1998). Reduced efficacy to ~50% after one year with “single-shot vaccines” is still a significant limitation for both gonadotropin-releasing hormone-based (Gionfriddo 2011) and porcine zona pellucida-based (Rutberg et al. 2013a) preparations. Therefore, we concluded that the permanence and 100% effectiveness of surgical methods (MacLean et al. 2006) was necessary to assess the population-level impacts of deer management via fertility control.

We have demonstrated that permanently sterilizing >90% of female deer in 6 study sites resulted in annual population declines of 3-44%, with an average annual reduction of 18%. This level of reduction is contrary to most previous study projections when using fertility control treatments for managing deer in open environments (i.e., not wholly fenced areas or islands). Thus, our study has disproven the previous perceptions of the infeasibility of treating enough females or the risk of extensive immigration when considering fertility control programs. We found similar rates of annual population decline as were documented in island or fenced environments (Naugle et al. 2002, Rutberg and Naugle 2008, Rutberg et al. 2013b). Of our study sites, only NIH and VGCC had security fencing, and neither fence prevented deer from entering or exiting. We had deer both immigrate and emigrate regularly from NIH, and our tagged and radio-collared deer at VGCC were often observed outside of the property. We reduced the local deer population by ~73% over 7 years at VGCC by sterilization alone. The program has been so successful at meeting the community's deer population goals that some residents are now concerned that the population will be reduced too low. This is an improbable outcome based on previous expectations of fertility control methods for managing deer populations. As noted by Grund (2011), nearly all females need to be treated in populations with high annual survival rates (>90%) to achieve a population decline. With nearly 90% treatment rates, we barely obtained an 8% population reduction from Year 2 to Year 3 in CLIF, and only 28% over 4 years. We only could account for 2 radio-collared female mortalities, out of 17 collared, over the first 3 years.

We selected research locations based on the fundamentals outlined by Garrott (1995) and Rudolph et al. (2000) that emphasized the need for extensive access and approachable deer. Mobile darting (i.e., darting from a vehicle on public roads) was critical in all case studies. By using an approach method that deer were exceptionally accustomed to, we were able to capture

nearly all the females before they fully recognized the threat and began to avoid our capture efforts (Kilpatrick et al. 1997). If we had used vaccines that required repeated treatments and only afforded 90-95% efficacy, it likely would have compromised our ability to capture and effectively prevent conception in enough females to achieve the significant population reductions we documented.

We captured 74% of the total females sterilized in the first year at each study site. As a result, fawn to adult female ratios diminished rapidly after the first year of treatments, significantly changing the local herd demographics. As a result of reduced fawn recruitment, there was an initial increase in the percentage of adult males after Year 1. This was not the result of immigration, but a proportional increase as the fawn age class diminished, increasing the percentages of both adult sex classes. We did not observe an increase in the number of adult males in any of our study sites. In fact, the abundance of adult males remained the same or decreased over time in all locations.

Overall, 74% of the sterilized females were captured in the first year and 87% in the first 2 years at each study site. Therefore, long-term maintenance and treatment costs are substantially reduced after the second year with few females to be treated annually. This also facilitates the rapid transition to local volunteers conducting field operations, if this is a program objective.

We often encountered females with home ranges that overlapped areas adjoining the defined study sites. When untagged females appeared subsequent to the capture and treatment efforts during Years 1 and 2, with high percentages of females tagged, it was rarely the result of immigration. Several of our radio-collared females that lived near the perimeter of the study sites were often found outside the study area. The same “edge” females would vary their presence/absence among years, resulting in intermittent presence and accessibility as noted for

general application of fertility control agents to wildlife by Garrott (1995), and for horses in particular by Garrott and Siniff (1992). After 2-3 years, we would eventually encounter these individuals during our time in the field and capture and sterilize them as well. This overlap occurred in all study sites but had negligible impacts on population declines.

Overall, we documented minimal immigration in all study locations except VCH, where we experienced fairly significant immigration as the population declined. Therefore, philopatric behavior in deer observed by Porter et al. (2004) was consistent in our study areas except for VCH. Seasonal (winter) movements of deer into VCH, with the establishment of new home ranges, appeared to be the cause. Most of VCH was west and south facing, which moderated temperatures, caused snow accumulation to diminish more rapidly, and offered preferred winter habitat. After the second year and a 39% population decline, we recorded 14, 9, 7, and 19 antlerless deer immigrating into the study area in subsequent years (2015-18). Nearly all immigrants were culled during the archery harvest or captured and removed by euthanasia, thereby restoring the treatment rates to >90% each year, which nearly eliminated fawn recruitment. There were approximately 7-19 immigrants each year once the population was reduced to ~140 deer (30.0 deer/km^2) and as low as 45 deer (9.8 deer/km^2). If we assume an overall annual mortality of 20%, based on the first 2 years of population decline without culling, then we would not be able to reduce the population below ~60 deer (12.9 deer/km^2) using surgical sterilization alone. On average, mortality would be negated by immigration, with 100% of the females sterilized. Sustaining the population at ~60 deer would require an annual effort to capture and sterilize all female immigrants.

Our VCH study site directly abutted the Cornell campus, where Boulanger and Curtis (2016) conducted their surgical sterilization research. Yet, we documented a completely different

outcome by using ovariectomies as our treatment. We demonstrated a 39% population reduction over 2 years prior to integrating lethal removal efforts and did not witness an increase in male deer abundance during camera survey population estimates or field efforts. This difference in outcome supports our contention that using tubal ligations is a flawed approach when assessing surgical sterilization as a fertility control technique to reduce local white-tailed deer populations where immigration is a risk. It is important to note that the archery culling program in VCH if used independently, would not have maintained the reduced population effect. We were only able to harvest 30-40% of the local population each year because of setback limits on archery tackle and learned avoidance behavior of deer. Without having nearly all the remaining females infertile, subsequent reproduction would have negated any short-term population reductions. This outcome also would have been the case for the research conducted by Boulanger and Curtis (2016), given their culling percentages. The final phase of the VCH program involved remote immobilization followed by euthanasia because of new restrictions imposed by a law that prohibited placing bait for deer within 91.5 m of a roadway. As a result, we only had 2 culling locations available, and it would have resulted in minimal impact on the remaining deer population. We took advantage of the vulnerability of deer to mobile darting in suburbia to capture and euthanize all but 9 deer, reducing the location density to 2 deer/km^2. We had not documented a limit on the population reduction potential of sterilization because of immigration in the other study locations.

To maintain capture efficiency when we attained high percentage capture rates, we used radio-collars placed on matriarchal females to track yet untreated females (Rudolph et al. 2000). We had minimal diminishing returns even when >80% of the females had been captured because we maintained engagement rates by readily locating untagged females. Radio-collar tracking, used in conjunction with mobile darting from public roads, was critical to the success of all

research projects. The effectiveness of mobile darting from the road was further demonstrated with all but 9 deer lethally removed from VCH in April 2018.

Behavioral changes associated with surgical sterilization treatment in Highland Park, Illinois, USA were noted with increased dispersal of treated females and increased mortality (Gilman et al. 2010). We had many female deer become unaccounted for, both collared and uncollared, but we could not always determine if they dispersed or died locally because they were never detected or recovered. We only tracked radio-collared females each year during subsequent capture sessions. We could not validate all mortalities of collared females, and therefore, could not differentiate our inability to locate collared female deer due to mortality (and disposal) or dispersal. Consequently, it was not possible to accurately quantify dispersal rates.

Overall, we experienced 15 mortalities while handling 570 deer, resulting in a 2.6% mortality rate for capture and surgery combined. The relatively high handling mortality rate at NIH was the result of training new veterinarians during the first 3 years and the extended surgical times (75 to 100 minutes; 3-4 times the typical amount of time with experienced veterinarians). At NIH, there was 1 post-surgical death in Year 1, 1 in Year 2, 1 in Year 3, and none in Years 4 and 5. If we removed the NIH training-related deaths, then our mortality rate was 2.0% (11/525).

A hybrid program with both culling/hunting used in conjunction with fertility control treatments, as we did in AA and VCH, might be the most cost-effective management approach (Garrott 1995). In AA, we documented similar rates of population decline in the first few years to the other study sites without culling. Longer-term data will allow us to assess whether culling in adjoining open spaces reduces immigration rates at lower densities.

Although fertility control programs can be costly, there are actual costs from doing nothing as deer-related impacts increase. In Fairfield County, Connecticut, it was estimated that

each household incurred an average of ~$900/year associated with DVCs, landscape damage, environmental impacts, tick treatments, and Lyme disease-associated medical costs (Arno and Viola 2010). In addition, the cost of management options is relative, given that lethal methods may be severely constrained in their effectiveness in the same location because of development density (AA, VCH, VGCC), social/political resistance (FC, NIH), logistical and technical limits of archery hunting (CLIF), or legal constraints (VCH). Therefore, in situations where lethal methods are very limited or not an option, fertility control methods are capable of reducing deer densities as low, or lower than archery hunting (Williams et al. 2013). We demonstrated deer reductions below the archery threshold in AA (11.6 deer/km^2), FC (2.4 deer/km^2), NIH (11.7 deer/km^2), and VGCC (17.0 deer/km^2). In some unique locations, when politics permit, the optimal solution may be combining lethal methods with fertility control treatments (VCH).

MANAGEMENT IMPLICATIONS

There are an increasing number of developed areas where lethal deer management options cannot meet the stated objectives. Although not a deer management panacea, high-percentage treatment via ovariectomy can significantly reduce local deer populations, especially in areas with substantial vehicle access and approachable deer, given most legal and social obstacles are not present. It may be necessary to incorporate lethal methods in combination with this approach, if possible, when immigration precludes meeting management objectives.

ACKNOWLEDGMENTS

We are appreciative of the cooperation, patience, and permitting by state wildlife agencies (California Department of Fish and Wildlife, Maryland Department of Natural Resources, Michigan Department of Natural Resources, New York State Department of Environmental Conservation, Ohio Department of Natural Resources, Virginia Department of Inland Game and Fisheries). Projects would not have been funded or authorized without the thoughtfulness of City Council members, local Board members, and local donors. We thank local law enforcement for assistance and oversight. Our research would not have been possible without cooperation and support from partners such as P. Curtis from Cornell University who was instrumental in the organizational and population estimation phases in VCH, the professional

staff at NIH for field and surgical support, and the Cincinnati Parks Department. We also are grateful for the support from numerous veterinarians, including Dr. K. Dyer, Dr. R. Junge, Dr. J. Newman, Dr. K. Ortved, and, most of all, Dr. S. Timm who helped refine the surgical procedure to make it both field efficient and humane. We thank the numerous local volunteers who were responsible for site preparations, trail camera monitoring, animal transport, veterinary technician support, and animal recovery monitoring. We also thank the many homeowners who allowed us to capture deer on their properties and the residents who supported our efforts in their communities. Finally, we are grateful to Dr. S. Williams for his review of an earlier version of this manuscript.

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Associate Editor:

Figure Captions

Figure 1. Delineation of focal white-tailed deer surgical sterilization study area in Ann Arbor, Michigan, USA.

Figure 2. Delineation of white-tailed deer surgical sterilization study area in the Clifton area of Cincinnati, Ohio, USA.

Figure 3. Delineation of white-tailed deer surgical sterilization study area in City of Fairfax, Virginia, USA.

Figure 4. Delineation of white-tailed deer surgical sterilization study area in National Institutes of Health, Bethesda, Maryland, USA.

Figure 5. Delineation of white-tailed deer surgical sterilization study area in the Village of Cayuga Heights, New York, USA.

Figure 6. Delineation of black-tailed deer surgical sterilization study area in the Villages Golf and Country Club, San Jose, California, USA.

Tables

Table 1. White-tailed deer surgical sterilization study site locations, field implementation dates, quantity of females sterilized, handling related mortalities, and the associated number of deer captured during each field session from 2012 - 2020.

Study site and field date[a]	Females sterilized	Mortalities[b]	Captures[c]
AA			
22-29 Jan 2017	49	0	52
2-6 Jan 2018	10	0	14
28-30 Nov 2018	1	0	1
22 Jan-20 Feb 2020	0	0	0
CLIF			
1-7 Dec 2015	41	2	44
16-19 Jan 2017	10	0	10
8-14 Jan 2018	8	0	11
24-27 Aug 2018	4	0	6
24-28 Jan 2019	7	0	9
1 Nov 2019-8 Feb 2020	9	1	10
FC			
31 Jan-6 Feb 2014	18	0	21
26-31 Jan 2015	18	0	20
14-16 Dec 2015	6	1	8
6-7 Dec 2016	5	0	5
16-18 Jan 2018	4	0	4
NIH			
14-16 Dec 2014	24	2	27
2 Dec 2015	5	1	5
3 Dec 2016	8	1	8
4 Dec 2017	2	0	2
8 Dec 2018	3	0	3
VCH			
1-15 Dec 2012	137	3	172
2-6 Dec 2013	11	0	13
26-27 Mar 2016	5	0	8
VGCC			

25 Jan-4 Feb 2013	99	4	107
8-12 Oct 2013	9	0	10

[a] AA = Ann Arbor, Michigan, USA; CLIF = Clifton area, Cincinnati, Ohio, USA; FC = City of Fairfax, Virginia, USA; NIH = National Institutes of Health, Bethesda, Maryland, USA; VCH = Village of Cayuga Heights, New York, USA; VGCC = Villages Golf and Country Club, San Jose, California, USA

[b] Includes capture and sterilization related mortalities.

[c] Includes females sterilized, recaptures, incidental male captures, and euthanasia (related to capture and preexisting conditions).

Table 2. Field staff/biologist and veterinary effort for 5 surgical sterilization study sites. Hours accrued for veterinarians are summarized as veterinary person-hours/deer sterilized (VET H/S), and hours accrued for field staff/biologists are summarized as field staff/biologist person-hours/deer captured (FB H/C). In CLIF, volunteers participated in prebaiting, site preparations, and transport of animals. Volunteers participated in pre-baiting and site preparations at FC. Volunteers participated in surgeries at NIH. These volunteer hours are not included, but overall represent minimal impact given the training and support needed to train volunteers.

	Year 1		Year 2		Year 3		Year 4		Year 5	
Study site[a]	VET (H/S)	FB (H/C)	VET (H/S)	FB (H/C)	VET (H/S)	FB (H/C)	VET (H/S)	FB (H/C)	VET (H/S)	FB (H/C)
CLIF	1.6	3.0	3.3	6.6	6.8	9.8	9.1	13.3	NA	15.0
FC	6.1	10.9	6.8	12.3	5.2	7.7	5.0	9.8	5.0	10.1
NIH	2.0	4.3	2.2	4.4	1.5	2.8	2.0	3.0	1.3	2.7
VCH	1.3	3.7	2.2	9.1						
VGCC	1.6	2.7	6.0	9.0						

[a] CLIF = Clifton area, Cincinnati, Ohio, USA; FC = City of Fairfax, Virginia, USA; NIH = National Institutes of Health, Bethesda, Maryland, USA; VCH = Village of Cayuga Heights, New York, USA; VGCC = Villages Golf and Country Club, San Jose, California, USA

Table 3. Population demographics derived from population estimates and field operations for 6 surgical sterilization study sites from 2012 - 2020.[a,b]

AA							
Survey date	**Survey type**	**Population estimate**	**Deer/ km^2**	**Adult females sterilized (%)**	**Fawn/adult female ratio**	**Antlered males**	**Antlerless immigration**
4-12 Feb 2017	BCS	94	21.9	90%	1.1:1	6	-
7-22 Jan 2018[c]	BCS	70	16.3	96%	0.2:1	11	1
1-13 Dec 2018[d]	BCS	54	12.8	97%	0.1:1	13	1
22 Jan -20 Feb 2020	BCS	50	11.6	88%	0.1:1	11	2

CLIF							
Survey date	**Survey type**	**Population estimate**	**Deer/ km^2**	**Adult females sterilized (%)**	**Fawn/adult female ratio**	**Antlered males**	**Antlerless immigration**
8-26 Dec 2015	BCS	99	41.3	86%	0.6:1	32	-
19-29 Jan 2017	BCS	83	34.6	89%	0.1:1	29	1
16-27 Jan 2018	BCS	80	33.3	91%	0.1:1	23	1
3-24 Feb 2019	BCS	74	30.8	94%	0.2:1	14	2
13-28 Feb 2020	BCS	72	29.9	98%	0.1:1	16	1

FC							
Survey date	**Survey type**	**Population estimate**	**Deer/km^2**	**Adult females sterilized**	**Fawn/adult female ratio**	**Antlered males**	**Antlerless immigration**

				(%)			
20-30 Jan 2014	NBCS	91	5.5	31%	1.3:1	6	-
1-11 Feb 2015	BCS	66	4	91%	0.5:1	9	-
29 Nov-13 Dec 2015	BCS	53	3.2	93%	0.2:1	16	0
7-20 Dec 2016	BCS	48	2.9	84%	0.1:1	15	1
17-26 Jan 2018	BCS	40	2.4	91%	0.2:1	13	0

759

NIH							
Survey date	**Survey type**	**Population estimate**	**Deer/ km^2**	**Adult females sterilized (%)**	**Fawn/adult female ratio**	**Antlered males**	**Antlerless immigration**
14-16 Dec 2014	CC	47	39.2	100%	1.4:1	11	-
12-13 Dec 2015	CC	30	25.0	100%	0.1:1	7	5
2-3 Dec 2016	CC	24	20.0	100%	0.1:1	3	8
1-2 Dec 2017	CC	23	19.2	100%	0.0:1	5	1
7-8 Dec 2018	CC	25	20.8	100%	0.1:1	4	5
21 Nov 2019	CC	14	11.7	89%	0.0:1	4	1

760

VCH						
Survey date	**Survey type**	**Population estimate**	**Deer/km^2**	**Adult females sterilized (%)**	**Fawn/adult female ratio**	**Antlerless immigration**
4-12 Jan 2013	BCS	225	48.9	99%	0.6:1	-
17-24 Jan 2014	BCS	160	34.8	98%	0.03:1	3

6-13 Jan 2015	BCS	137	29.8	100%[e]	0.04:1	14
18-25 Jan 2016	BCS	68[e]	14.8[e]	100%[e]	0.1:1	9
12-19 Dec 2016	BCS	45[e]	9.8[e]	91%[e]	0.02:1	7
2-8 Apr 2018	PR	9[e]	2.0[e]	71%[e]	0.3:1	19

VGCC							
Survey date	**Survey type**	**Population estimate (95% CI)**	**Deer/ km^2**	**Adult females sterilized (%)**	**Fawn/adult female ratio**	**Antlered males**	**Antlerless immigration**
7-8 Sep 2010	DS	80 (48-95)	29.6	-	1.0:1	-	-
9-11 Oct 2012	DS	169 (105-223)	62.6	-	0.9:1	-	-
1-4 Feb 2013[f]	PR	140	51.9	100%	0.9:1	40	0
8-12 Oct 2013	PR	128	47.4	100%	0.2:1	37	2
5-9 Nov 2014	PR	102	37.8	100%	0.0:1	30	0
20 Sep-4 Oct 2015	CC	86	31.9	100%	0.0:1	23	0
17-26 Oct 2016	CC	75	27.8	100%	0.0:1	18	0
20 - 28 Aug 2017	CC	59	21.9	100%	0.0:1	10	0
1-17 Oct 2018	CC	56	20.7	100%	0.0:1	6	0
1-31 Aug 2019	CC	46	17.0	98%	0.02:1	6	1

[a] BCS = Baited camera survey; CC = Complete census; DS = Distance sampling; NBCS = Non-baited camera survey; PR = Population reconstruction

[b] AA = Ann Arbor, Michigan, USA; CLIF = Clifton area, Cincinnati, Ohio, USA; FC = City of Fairfax, Virginia, USA; NIH = National Institutes of Health, Bethesda, Maryland, USA; VCH = Village of Cayuga Heights, New York, USA; VGCC = Villages Golf and Country Club, San Jose, California, USA

[c] 7 adult males were culled after the survey on nearby properties.

[d] 8 adult males were culled after the survey on nearby properties.

[e] Post cull estimates.

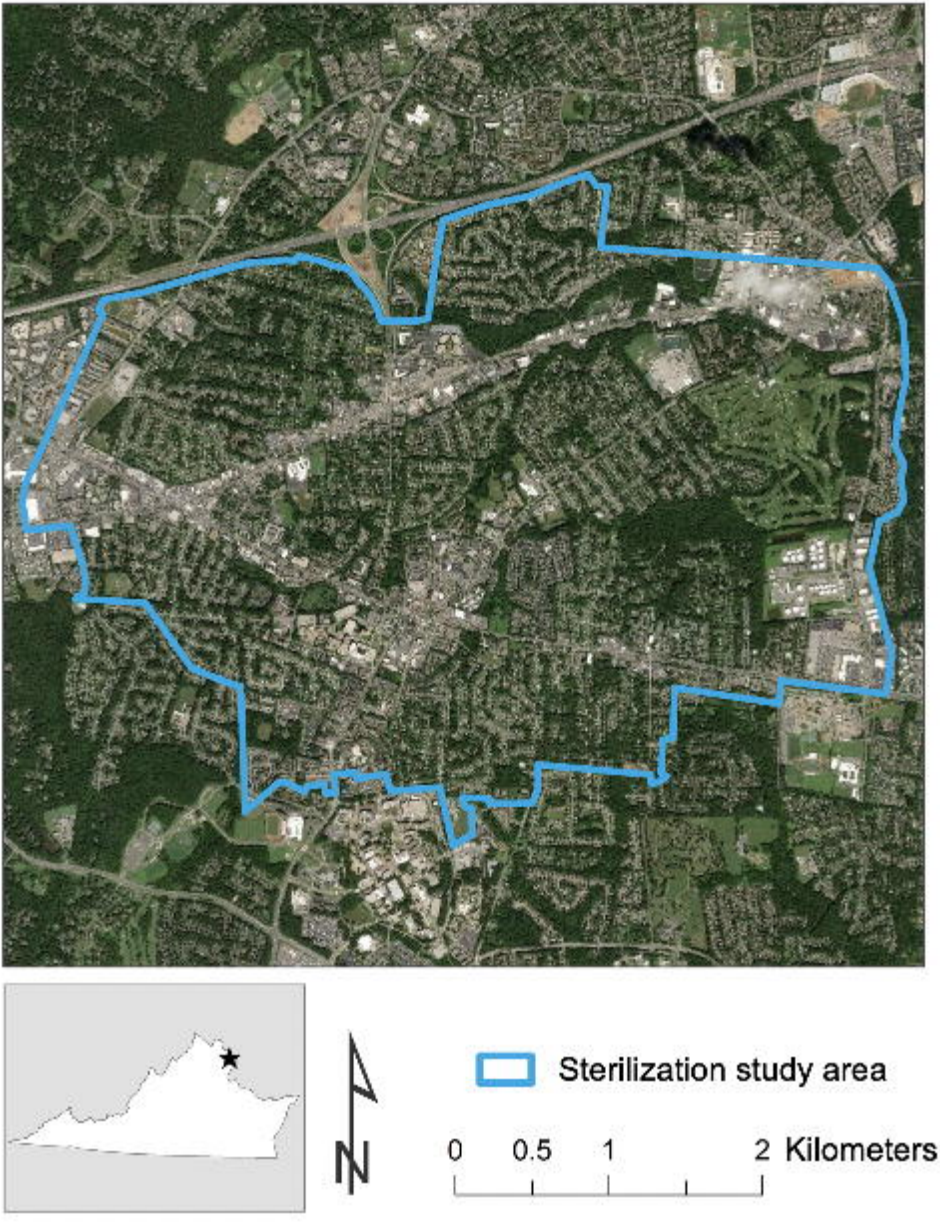
[f] Population estimate does not include 30 deer relocated to outside of the fenced area. Fawn/adult female ratio based on initial population of ~169 deer.

Table 4. Annual cull data segregated by tag status (e.g., tagged/sterilized), sex and age, on Village of Cayuga Heights, New York, USA, from 2015 to 2018.

Cull date	**Cull type**	**Total culled**	**Adult female (tagged)**	**Adult female (untagged)**	**Fawns**	**Antlered males**
6-14 Mar 2015	Archery	48	26	10	5	7
4-25 Mar 2016	Archery	24	13	5	4	2
2-23 Mar 2017	Archery	13	8	3	1	1
2-8 Apr 2018	Dart/Euthanasia	45	18	15	9	3

Sterilization study area
0
0.5
1 Kilometers
N

Sterilization study area
0
0.25
0.5 Kilometers
N


Sterilization study area
0 0.5 1 2 Kilometers
N

Sterilization study area
N
0
0.25
0.5 Kilometers

Sterilization study area
N
0
0.25
0.5
1
Kilometers

Sterilization study area
0 0.25 0.5 1 Kilometers
N