The Use and Efficacy of Trap-Neuter-Return for Feral Cat Management, Using Beijing, China, as an Example

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The management of feral cat (free-roaming domestic cats) is a growing global issue. In contrast to Beijing considerable feral cat population, feral cat management in the city has been poorly documented. Hence, the present study aims to specify the optimal approach of park feral cat management in Beijing, and extend it to other metropolises around the world. A population model was constructed and applied to analyze the efficacy of trap-neuter-return (TNR) programs on a hypothetical park population consisting of 100 individuals, with surrounding communities cleared of feral cats. Results were analyzed to examine feral cat population growth under the unsaturated environmental conditions, the efficacy of 75% TNR programs under such conditions, and the effects of timing and target age class on TNR programs' success of feral cat population restraint. This research concludes that: (1) A park population with surrounding communities cleared of feral cats increases drastically and reaches more than 200 times its initial size in five years; (2) In contrast to prior research on more saturated populations, no 75% TNR program is able to restrain the hypothetical park population; (3) The efficacy of TNR varies significantly with different timings and target age classes; TNR effect and efficiency, as well as the consistency of the two, are maximized in December and November, and targeting adult cats, while falling significantly under other combinations. Such conclusions suggest that TNR programs must be implemented in November or December on adult cats, in multiple months each year or with neutering rates higher than 75%.

Keywords: feral cat management, trap-neuter-return (TNR), Beijing (China)

Introduction

Definition of "feral cat"

Unowned domestic cats are usually referred to as feral or stray cats[1]. Although some authors give different definition to feral cats and stray cats based on the extent of their wildness and aversion to humans, they state that the line between the two categories is blurred, and individual cats may be classified to each category in various stages of life[2]. Feral cats are defined as domestic cats that are unconfined, not attached to a particular household, and with no specific "owner", despite sometimes living close to and fed by humans[1–3]. The present research utilizes this definition and addresses all unowned domestic cats as feral cats.

Significance of feral cat management

Feral cats are a major issue to management and conservation worldwide[4], recognized to have a significant impact on biodiversity and ecosystem, human health and production, and animal welfare[1,5]. Therefore, the management of these animals is of great importance.

Beijing holds a large feral cat population, estimated to consist of 200,000 individuals[6,7], reaching a partial density of 64 cats per kilometer squared[8]. These are considerable estimates compared to the figures from other areas, such as the 1.13 million cats in whole New Zealand with a partial density of between 1.06 and 1.19 cats/km^2 in a semi-urban park[9], and the 1,858 cats with a density of 13.3 cats per km^2 in Windsor (USA)[10]. The presence of such a large and dense feral cat population in Beijing makes the animals' scientific management a significant factor for the quality and sustainability of the city's urban ecosystem and human life.

Why TNR?

A wide variety of approaches have been devised for feral cat eradication. These approaches often aim for decrease in reproduction, increase in mortality, adoption, or relocation.

Trap-neuter-return (often known as TNR) is a praised operation for decrease of cat reproduction, involving the trapping and neutering of feral cats before tagging and releasing them back to their original location or into a colony, ideally fed by volunteers[11]. A relatively ethical approach to eliminate cat reproduction, TNR became popular in the 1990s[11,12], and has been practiced on various sites: in China, TNR is so widely publicized that some high school and undergraduate students are actively organizing TNR throughout the country[13–15]; in the USA, TNR was very popular at a time and some carefully managed colonies were established on public land[12]; South Africa, Denmark, the UK, Canada, and the Netherlands are also known to have conducted TNR operations1. Positive effects are reported from these sites, and TNR's popularity isn't decreased by the discovery that, besides being comparatively ethical, it is proven to improve feral cat body conditions and enhance fat accumulation, probably via making them less likely to roam[16].

Criticism on TNR does exist. Some doubts are raised on the efficacy of TNR in controlling feral cat population. For example, some authors reported that feral cat number in their study areas either increased or remained constant under TNR operation, and the established cat colonies encouraged illegal dumping of pet cat[12]. Statistical analysis demonstrated that only a >75% neuter rate could reduce cat number or at least achieve a stable number[17]. Opponents of TNR also argue whether TNR is really humane, for potential casual and irresponsible colony management could lead to animal cruelty[1].

In spite of the criticisms, there are still a considerable number of reports that indicate TNR's success in deduction of feral cat population. Kreisler et.al. documented "decrease in population size and increase in welfare" under a 23-year feral cat TNR program in a 10-km^2 community in Florida, USA[18]. TNR program in the University of Central Florida is reported to lead to an 85% decline of campus feral cat population over a period of 28 years, despite the university's growing enrollment and presumable increase in refuse food[19]. Several other TNR programs from multiple sites are also reported to lead to feral cat population deduction and shelter intake[20].

There are other alternatives for sterilization. One of them is nonsurgical contraception, which often involves blocking cat fertility using vaccines that can immunize certain fertility pathways, such as fertilization of ova in females or gonadotrophin-releasing hormone (GnRH) in males[1]. This approach is appraised to be "a realistic future goal" for feral cat management.

Another approach to decrease cat reproduction is known as trap-vasectomy/hysterectomy-release/return (TVHR), which differs from TNR by sterilizing the cats through vasectomy or hysterectomy on females[21]. Cats that have gone through this process still produce sex hormones and exhibit sex behaviors, but possess no fertility[21]. Modeling demonstrates that TVHR actually performs more cost-efficiently than TNR in reducing cat population size[21], although it is noted that this approach doesn't eliminate cat fertility as reliably as TNR1.

The most common approach to increase mortality is euthanasia. The number of un-owned cats euthanized each year is estimated to be 0.86 million in the USA alone, 11% to 54% of all the cats entering shelters annually[22,23]. Statistical modeling showed that an annual 50% euthanasia leads to a 10% cat population reduction per year, which is more efficient than TNR[17].

Another approach of heightening mortality, on-site killing, usually involves poisoning[1,11]. Poisons often include carbon monoxide, sodium pentobarbital, anticoagulants, and sodium monofluroacetate[1,11]. Means other than poisoning have also been proposed, and in some cases, practiced. For instance, in 2005, the Wisconsin Conservation Congress proposed to change the protection status of free-roaming cats and make them legal game for hunters, yet the proposal was struck down by voters[11].

In spite of their relatively high efficiency, numerous doubts have been raised on the ethicality of such killing approaches. For instance, most cats euthanized are found to be in perfect body conditions, having shiny pelages, without any visible injures or other sufferings, and carrying no serious disease[1]. Poisoning is another heavily criticized technique, because it is very likely to poison un-targeted animals[1]. Research showed that 221 of Australia's 3,769 native vertebrate species are likely to consume cat-baits, most of them birds[24], whose protection is one of the main reasons to eradicate cats[1]. Moreover, birds are much more vulnerable to poisons than mammals, and non-target poisoning deaths are most frequent in wild predatory birds[25].

Adoption programs are often run alongside TNR operations or capture-euthanasia, in which captured cats that are fit for adoption are advertised for adoption, and those that aren't adopted are eventually released into colonies or euthanized[4,17]. It is reported that although most feral cats are too wild to be adopted[2], adoption programs run alongside TNR have resulted in good consequences[17].

It is also proposed to trap feral cats and relocate them to other, more appropriate locations, which may involve establishing cat sanctuaries[1]. This approach is described by some authors to be "expensive to run and only able to care for a small percentage of cats" and "unable to work as a sole technique"[1].

In conclusion, despite their lower efficiency compared to increased mortality, TNR, nonsurgical contraception, and TVHR provide better safety to the ecosystem and hold the better ethical consideration. Therefore, this research focused on approaches that aim to decrease cat reproduction. Among the three approaches, TNR is targeted in this research for its more extensive documentation found in literature, which provided better references to this research's methods, although it shall be noted that this situation may not maintain as other similar methods continue to sophisticate.

The goal of this research

The academic attention on feral cat management is usually directed towards their population reduction or complete eradication[1,12,17,21,26]. An analysis of literature, however, stands against the complete removal of the animals.

Despite feral cats' preying upon a large number of prey[5,17,21,26,27], urban ecosystems could suffer from even worse consequences if feral cats are completely eradicated. An influential study proved that when a mesopredator, such as a rodent, is present, the disappearance of cats could lead to the rampant growth of the mesopredator population and hence a greater reduction of bird number even to extinction[28]. The authors further argued that despite being less proficient in hunting, rats give no less hunting pressure on bird population than cats, due to rat's much higher rate of reproduction[28]. In the authors' simulation, the rat population alone reduced bird population even more than the cat population alone, and had been claimed guilty for more than half of the extinctions traced to predators, more than two times the extinctions cats had caused[28]. Revisiting the topic, some authors devised a more sophisticated model and showed that the eradication of cats could certainly lead to more negative impact on birds than with the presence of cats, resulting in bird extinctions in the worst circumstances[29]. This is a phenomenon known as mesopredator release, on which a mesopredator's outburst follows the removal or the superpredator, and the population of their shared prey become subsequently diminished[30]. The cat-rat-bird relationship described by Courchamp (1999) is the original indicator of this effect[30], and the effect has been proved to commonly take place as apex predator populations are decreasing worldwide[31].

Feral cats are important cultural or historical symbol and tourist attraction of many places. Authorities of the Forbidden City (Beijing), for instance, claimed that the approximately 200 feral cats there are descendants of royal pet cats, and should be valued as "living historical relic"[32]. The Forbidden City Museum has derived various drawings and sculpture exhibitions from its feral cats, using the cats' cuteness as inspirations of art creation and tourist attraction[32]. The feral cats in the Nanjing Presidential Office, too, are believed to have attracted more tourists to the place, though less famous and less well-treated than their counterparts in the Forbidden City[33].

Furthermore, the presence of feral cats near people and the visibility of humane management to them can promote public acceptance to our responsibility to animals, as well as provide people with opportunities to observe the unconfined behaviors of a felid[1,3].

In conclusion to the various ecological, hygienic, and cultural advantages of feral cats, it seems a fair argument to retain a certain level of feral cat population. Therefore, this research proposes a new stand to balance between feral cat culling and conservation.

Due to zoonotic and welfare issues feral cat bring, it is a rational decision to continue the efforts put into their removal from Beijing's communities, as well as communities of other metropolises. However, because of feral cats' ecological and cultural values, it is necessary to allow the continuing existence of certain park populations, such as the 200 or so population in the Forbidden City (Beijing). With the surrounding communities all cleared of feral cat, these remaining park populations in an environment highly unsaturated, with an environmental carrying capacity far higher than the existing population. Given the proliferative reproductivity of domestic cat under low environmental pressure[1], such populations will raise great challenges to artificial population restraint.

With results from a feral cat population model, this research provides information on TNR efficacy in the context of such a hypothetical park population, and helps to meet the challenge of keeping such populations from expanding and spreading into surrounding communities. The information on the effects of timing and target age class will support future TNR programs to maximize efficacy and minimize cost in achieving the goal of keeping feral cats within park boundaries.

Because data of environmental carrying capacity and typical park feral cat population specific to Beijing, China, is integrated in the study's model, this study's results are best applied to feral cat management in Beijing, and provide example information for management in other metropolises under similar conditions.

Results

The control

Simulations illustrate that, without any TNR operation, on average, a feral cat population of 54 females would increase sharply and become a population with 12408.5 females in five years, 229.8 times the initial number, and peaking in May of the fifth year with a population comprising 24016.4 females (see Fig 1).

The average result of the simulations without TNR is applied as a control in later analysis, and is referred to as "the control" in the rest of the paper.

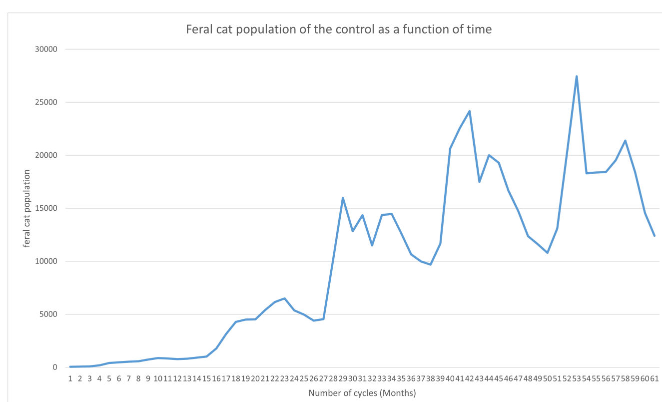

Fig. 1 Feral cat population of the control as a function of time.

Timing’s effect on TNR average difference and neutering efficiency index, and its variation among age classes

Among TNR programs targeting all three viable age classes, difference in timing induces significant variations in average difference and neutering efficiency index. The pattern of such variations however, is unique to each of the three age classes, and every month has distinctive ranking in each of the classes.

Adult TNR

See Fig 2 and Fig3, among TNR programs in the twelve months, TNR in December achieves both the highest average difference and neutering efficiency index. TNR in November achieves roughly the same population restraint in the first 52 months, but the population then grows with a much higher rate, and finally results in 1.61 times the ultimate population of TNR in December, and achieves 95.9

Average difference and neutering efficiency index have similar patterns among adult TNR programs with different timing, and the two measurements mainly different in extent skewing. Both measurements peak in December, and decrease on either side. Neutering efficiency index is considerably more skewed, with December and November standing conspicuously out, while the third highest month achieves only 48.1% that of November’s, and the fourth highest only 38.8%. Average differences across different timings, in contrast, skews less, with December and November less conspicious, the third highest 85.6% of November’s, and the fourth 81.5%.

Juvenile TNR

See Fig 2, juvenile TNR’s average difference peaks in March conspicuously, with 1.38 times the figure of the second highest month. The rest of the months show a less obvious pattern, decreasing on both sides of March, and exhibiting another peak in June and July, which achieve 68.3% and 72% the average difference of March, respectively. Also exhibited are two sharp decreases of average difference in August and November, where the average differences fall below 10% of the third lowest month.

See Fig 3, neutering efficiency index peaks in December, followed by January, March, and February. The pattern of this measurements shows a noticeable skew from TNR in winter and spring to TNR in summer and Autumn, still with the two sharp decreases in August and November.

Kitten TNR

In the case of kitten TNR, average difference and neutering efficiency index both shows three peaks among the twelve months of a year, and the peaks of the two measurements aren’t as consistent as those of adult TNR either (see Fig 2 and Fig 3).

Average difference peaks in March, June, and November, with June being the highest peak and November the lowest, while neutering efficiency index peaks in January, June, and November, with January the highest, and June the lowest. Fluctuations are clearly shown among both sets of peaks, average difference and neutering efficiency index both exhibiting significantly decreased magnitude between two peaks (see Fig 2 and Fig 3).

Fig. 2 Average difference across TNR programs with different timings and age classes. Labels on the X axis refer to the months’ sequence in a year. For example, “1” is January.

Fig. 3 Neutering efficiency index across TNR programs with different timings and age classes. Same as Fig 1, labels on the X axis refer to the months’ sequence in a year. For instance, “1” is January.

Age class's effect on TNR average difference and neutering efficiency index, and its variation among age classes

Among the three viable age classes, TNR targeting adults achieves the distinctly highest average difference and neutering efficiency index. The seven highest average differences are all generated by adult TNR programs, so as the five highest neutering efficiency indexes. On average, adult TNR generates an average difference 3.90 times juvenile TNR and 2.62 times kitten TNR; while its average neutering efficiency index is 4.12 times that of juvenile TNR and 7.20 times that of kitten TNR.

Juvenile TNR outperforms kitten TNR on average difference, achieving, on average, 1.75 times that of kitten TNR; juvenile TNR's neutering efficiency index, however, is lower than kitten TNR by 32.8

Consistency of average difference and neutering efficiency index

Average difference and neutering efficiency index have a high level of consistency in adult TNR. Eight of the twelve months have the same rankings in both average difference and neutering efficiency index among adult TNR programs, and the four months that have different rankings in the two measurements all fall within two places.

Juvenile and kitten TNR, however, have less robust relationships between average difference and neutering efficiency index. Among juvenile TNR programs, only two months have the same ranking in average difference and neutering efficiency index, while in the other ten months, there are two months that have the two rankings different by six places, one month by four places, and two months by three places. Among kitten TNR programs, also only two months have same rankings in average difference and neutering efficiency index, and the other months include one that has the two rankings different by eight places, and three that have the rankings different by three places.

In the cases of juvenile and kitten TNR, TNR programs with high average differences tend to have lower rankings in neutering efficiency index. Juvenile TNR programs with the highest to the fifth highest average differences all falls in ranking in neutering efficiency index; the same happens to the TNR programs that achieve the highest, second highest, and fourth highest average differences. Programs with low effectiveness ranking, on the contrary, sometimes jumps in efficiency ranking.

Evaluation of TNR's effect on a highly unsaturated population

TNR programs with different timings and target age classes nearly all achieve positive average differences. The only exception is kitten TNR in December, which is predicted to have negative average difference (see Fig 2). Average differences of all the tested TNR programs have a medium of 2073.0, an average of 2916.2, a maximum of 8672.4, and a minimum of -147.9. It is noticeable that 33 of the 36 TNR programs achieve an average difference higher than 622.9, while the other three programs only have a maximum of 56.0, 9% of the rest 33 programs' minimum.

See Fig 4, Fig 5, and Fig 6, no single TNR program tested is able to retain initial feral cat population. The lowest ultimate population of 2409.9 females is generated by adult TNR in December, so is the lowest peak in five years, a population with 3133.9 females in June of the fifth year, 44.6 and 58.0 times of the initial population, respectively, and 19.4% and 13.0% of the control's, respectively. The peak of the population under adult TNR in December comes one month later than the control.

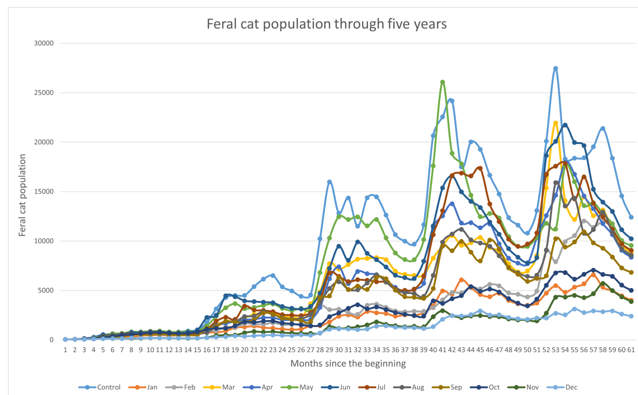

Fig. 4 Feral cat population under different adult TNR programs as a function of time.

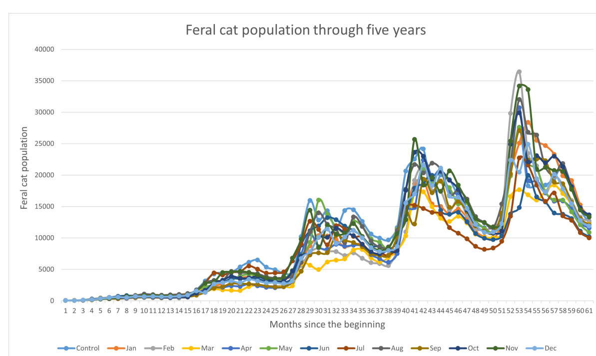

Fig. 5 Feral cat population under different juvenile TNR programs as a function of time.

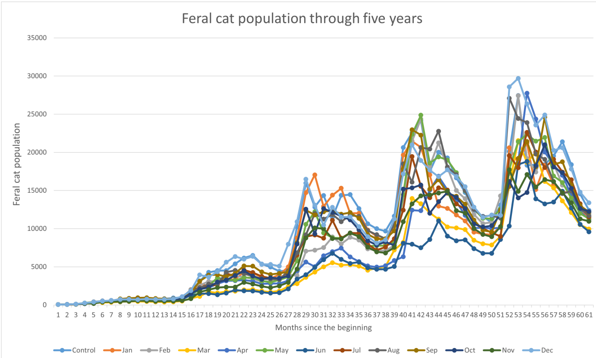

Fig. 6 Feral cat population under different kitten TNR programs as a function of time.

Methods

Research design

A computer female-only cat population model was constructed to simulate feral cat population. The model was run under TNR programs with different timings and target age classes, and monthly feral cat populations were recorded and analyzed to evaluate the efficacy of different TNR programs.

Data collection

For simplicity, the feral cat population model in this research only considers the female population. Female-only feral cat population models work under the assumption that males are always abundant, and such models have been applied and justified in similar research aiming to predict success of feral cat population control[6,17,21]. Shown below are the structure, equations, factors, and data involved in the model of this research.

Cycles of the simulation model

The simulation model returns a new population size every cycle, and each cycle represents a month. Every cycle the new population size is calculated through a simple equation:

$$p\_n1 = birth - death$$

Where p_n1 is the feral cat population at the end of the cycle (month), birth is number of kittens born in the cycle (month), and death is number of deaths that occur within the cycle (month). The number of new born kittens and deaths are calculated in each cycle based on the current size, breeding capacity and month mortality specific to each of the four age classes: kitten, juvenile, adult, and senior. Individuals reaching the upper age boundary of their age classes are categorized in the subsequent age class at the end of each cycle (month). Kittens born in a cycle (month) times cycle-specific kitten mortality are added to kittens at the end of the cycle (month).

Age-class-specific breeding capacities, mortalities, and environmental carrying capacity

Based on the breeding capacity unique to each life stage of a domestic cat, the four age classes were defined in a prior modeling research of feral cat population in the UK[34]. The specific breeding capacity, mortality, and initial population percentage of each age class was also extracted from the open-access data provided by the definers. Research demonstrated that domestic cats do not usually breed until they reached six months of age, a portion breed between six months and a year of age, reach sexual maturity at their first birthday, and are expired from breeding over eleven years old. Cats younger than six months are categorized as kittens and possessed no breeding capacity; cats between six months and one year of age are classified as juveniles, a portion of which breed; adults, mature cats in their breeding age, between one and eleven years of age, are all expected to breed; and cats older than eleven years are seniors, with zero breeding capacity same as kittens[34].

The breeding capacity of each age class was expressed as number of female offsprings generated per pregnancy:
Kitten: 0
Juvenile: lsi * pregon * fera * jbreind
Adult: lsi * pregon * fera
Senior: 0

Where lsi is litter size (a random factor between 1 and 6)[35,36], pregon is rate of maintained pregnancy (0.918)[36], fera is female ratio at birth (a random factor between 0 and 1), and jbreind is rate of juveniles that breed (a random factor between 0.5 and 1)[36,37]. The figures of these factors correspond with former field studies on domestic cat reproduction performance in France, although notably they may exhibit variation due to change in locality, and may potentially be a source of uncertainty.

In the data from the definers, the age-class-specific month mortalities are:
Kitten: 0.19;
Juvenile: 0.08;
Adult: 0.04;
Senior: 0.10.

In the research in UK that defined the four age classes, these data were formulated so that they correspond to field data in Italy, Australia, and the USA, under the assumption that they could also be applied on feral cat in the UK[34]. The present research further assumed that the mortalities could also be applied to feral cat in Beijing, and they are feral cat mortalities under optimal conditions[26]. Uncertainty in these assumptions or local variation in these parameters may affect the success of age-class-specific

TNR programs to some extent.

The age-class-specific month mortalities applied in the model is added with the influence of the environmental carrying capacity (referred to as "carrying capacity" in the rest of the paper), following a formula formulated in a prior modeling analysis of feral cat population[26]:

$$m = m0 - (m0 - m1) * p/k$$

Where m is the age-class-specific month mortality of that particular cycle (month), m0 is the age-class-specific month mortality under optimal conditions (as shown above), m1 is the age-class-specific month mortality when population is at carrying capacity, p is the population at the beginning of the cycle (month), and k is the carrying capacity.

It is assumed that month mortalities at carrying capacity are 1.0, 0.8, 0.5, and 1.0 for kitten, juvenile, adult, and senior, respectively, as was the expectation of some similar prior research[17,26]. It should be noted that these parameters are not formulated upon substantial field data, so that they may lead to a certain extent of uncertainty on the simulation results, and variation of these parameters may influence the success of age-class-specific TNR programs.

The carrying capacity is set as the current female feral cat population in Beijing, assuming that the present feral cat population is at saturation. This is the formula by which the carrying capacity is calculated:

$$k = p\_e * 0.56$$

Where p_e is the estimated current population of Beijing (200,000 cats)[6,7], and 0.56 is the estimation of female ratio in urban feral cat populations based on the ratio of female/male territory size per cat[3], under the assumption that females and males occupy the same territory size in total.

Seasonality of reproduction

Seasonality of reproduction is expressed by the average frequency of pregnancy per cat during a cycle (month). The followings are average frequency of pregnancy per cat estimated by a long-term field study on feral cat reproduction[37]:
January = 0.07
February = 0.18
March = 0.57
April = 0.68
May = 0.45
June = 0.25
July = 0.25
August = 0.17
September = 0.16
October = 0.08
November = 0.01
December = 0.04

These parameters correspond to the results of the simulation study in the UK[34], although it shall be noted that these parameters, like age-class-specific mortalities and breeding capacity, may provide uncertainty due to local variation, since they are based on a field study in France whereas this study uses Beijing as an example.

TNR

Age classes viable for TNR are kitten, juvenile, and adult, since seniors have ceased reproducing. A specific neutering rate of a viable age class can be added to any of the twelve months of a year, and the neutering would take effect two month later, approximately the length of domestic cats' average gestation period (65 days)[34].

In the model, feral cats neutered lose their fertility permanently, but are still counted in the population and have the same month mortality as un-neutered cats in the same age class.

For each tested TNR program, a set neutering rate is repeated on the target age class in the same month every year. The neutering rate refers to percentage of fertile members of the target age class to be neutered. Infertile individuals are not counted. Because of the difference in total population every year, the number of cats neutered under the same neutering rate could vary from year to year.

Initial population

The initial population is consistently 54 females, the estimated number of females of a park population of 100 individuals. Female ratio in the population was calculated via the same method used for the carrying capacity. This ratio in parks (0.54) is slightly lower than in the whole urban area (0.56), which is applied in the estimation of the carrying capacity[3]. The park population of 100 individuals was formulated on data from the Forbidden City and other two celebrated public parks in downtown Beijing, Tiantan and Zizhuyuan, which host an estimated feral cat population of 90, 80, and 200, respectively.

Immigration and dispersal

The context of this study is the elimination of feral cat in communities and maintaining within parks, so that an isolation to the simulated park population is assumed. Because of this context, immigration and dispersal are not included in the model. The potential influence of the exclusion of these factors is addressed in the discussion section.

Data generation

For each run of the simulation model, the female feral cat population was recorded every cycle (month) through 60 cycles (5 years). The total number of cats neutered all through the 60 cycles (5 years) was also recorded.

The simulation was run ten times for each of the TNR programs tested, generating varied results due to the random factors in feral cat reproduction. For each TNR program, population at the end of each cycle (month) and total number of cats neutered were the average of the ten runs.

The control

Discussed in more details in Results, the control's neutering rate is always zero for every cycle (month). No cat is neutered through the 60 cycles (5 years).

Variables and measurements

Independent variables:

1. TNR timing: the month in which a tested TNR program takes place.

2. TNR target age class: kitten, juvenile, or adult. Every possible combination of the two independent variables were tested.

Control variable: Neutering rate: 75% for all simulations, which is the estimated minimum neutering rate that is able to cause reduction of feral cat population in the US[17].

Dependent variables:

1. The feral cat population size (female only) at the beginning and at the end of each cycle;

2. The total number of feral cats neutered.

Measurements:

1. Average difference: for every simulation of a TNR program, the average difference between the population at the end of each cycle (month) and the population at the end of the same cycle (month) of the control. This is a measurement to evaluate the effectiveness of a TNR program.

2. Neutering efficiency index: for every simulation of a TNR program, average difference / number of cats neutered * 100. This is a measurement to evaluate the efficiency of a TNR program.

Procedure

1. Ran the simulation model for TNR programs with every possible combination of timing and target age class, collected data as described in data collection;

2. Calculated the average difference and neutering efficiency index for every tested TNR program;

3. Visualized and compared the average difference, neutering efficiency index, and population change of the tested TNR programs.

Data analysis

1. To compare the efficacy of different TNR programs tested, average difference and neutering efficiency index were compared across programs using a combination of graphs and data. Bar graphs were created using excel for average differences and neutering efficiency indexes across TNR programs. The two measurements are compared and contrasted via visually analyzing trends shown in the graphs and comparing data records.

2. To evaluate the efficacies of the various TNR programs tested, the initial population and population at the end of each cycle (month) were plotted on line charts as a function of number of cycles (months). The line charts were created also using excel, and were also analyzed through visual analysis of the line charts and consultation of the data.

3. The consistency of average difference and neutering efficiency index was evaluated via comparing different TNR programs' rankings of the two measurements within programs with the same target age class.

Participants or samples/ethical considerations:

No real-world experiment was conducted in this research. All data required for the construction of the simulation model was acquired from works cited. Therefore, this research concerns neither of the two topics.

Discussion

Key findings

The results of the current research demonstrate the drastic growth of feral cat population in a highly unsaturated environment, the efficacy of repeated 75% TNR programs in such context, effect of timing on TNR efficacy, and the effect of target age class on TNR efficacy and the consistency of TNR effectiveness and efficiency.

Results from the control demonstrate that, without manufactural population restraint, a feral cat population comprising 54 females could, on average, expand to a population with 24016.4 females in five years, 444.7 times its initial size. Results from the TNR program simulations suggest that 75% TNR generally provide restraint on the population's growth, and most programs generate significant differences with the control. The results also demonstrate, however, that no 75% TNR program is sufficient to retain the feral cat population around its initial size. Graphical analysis confirms that only a few adult TNR programs with specific timings could lead to obvious population restraint, and none could inhibit population growth.

Such results on the efficacy of 75% TNR are in contrast to former modeling predictions that a 75% reduction of breeding females would reduce the feral cat population in the US[17]. This suggests that a small feral cat population in an unsaturated environment requires much more TNR effort to be successfully restricted from expanding.

Timing has a significant impact on the efficacy of TNR targeting all of the three viable age classes, illustrated by the varied average differences and neutering efficiency indexes of TNR programs with different timings. Each of the three age classes exhibit a unique pattern of timing's influence. The effectiveness and efficiency of adult TNR both peak in December and decrease on both sides of the month, while juvenile and kitten TNR both exhibit multiple peaks in effectiveness and efficiency, and decrease between peaks.

Adult TNR has an efficacy significantly higher than juvenile and kitten TNR, generating the highest efficacies and with both its average effectiveness and efficiency higher than those of the latter two. The efficacies of juvenile and kitten TNR are more difficult to compare, since juvenile TNR leads to a significantly higher effectiveness but an also significantly lower efficiency.

Adult TNR also exhibits the highest consistency of effectiveness and efficiency, with most of its programs ranking the same in both measurements, and the programs achieving the highest effectiveness (December and November) maintaining their top ranks in efficiency. Juvenile and kitten TNR, in contrast, possess much less consistency between effectiveness and efficiency, with their top-ranking programs in effectiveness tending not to have consistently high efficiency, and programs with high efficiency not achieving top effectiveness.

Implications and significance

The results of this research indicate a population explosion of a small park population with its surrounding communities cleared of feral cat, and suggest optimal future implementations of preventing such explosions.

The comparatively higher requirement for the control of the park population simulated in this study demonstrates the challenge of population restraint in a highly unsaturated environmental, and enhance the significance to maximize the efficacy of TNR performed on isolated park populations.

It can be drawn from the results of this research that, in order to achieve the greatest effect and highest efficiency, as well as the greatest consistency of the two, feral cat TNR programs are optimally led out in December or November, and targeting adults only, whereas the efficacy of TNR with other timings or target age classes would reach results far less than these two combinations.

However, as demonstrated in this research, no single 75% TNR program is able to retain the size of a park population of approximately 100 cats, so TNR programs put into practice must have higher neutering rate or take place in multiple months.

Connection to objectives

The results are consistent with the expectation that timing and target age class would have an observable impact on the efficacy of TNR programs, and thus allows this research to fulfill its objective of analyzing the effect of these two conditions on TNR success.

Limitations and recommendations

This research only focuses on timing and target age class's effect on TNR efficacy, and all TNR program simulations are set with repeated TNR of a 75% neutering rate. While this allows this research to eliminate the effect of un-continuous TNR and varied neutering rate, it sets this research's results under the assumption that timing and target age class have the same impact regardless of whether the TNR program is repeated or un-continuous, and TNR efficacy is effectiveness is linearly proportional to neutering rate.

Moreover, the model of this research cycles in months, which accumulates errors gradually due to the large scale of each cycle. This may have resulted in amplified population fluctuations while the population simulations go on. To reduce the error, this research only analyzes simulation results within 60 cycles (five years), therefore latent effects in a longer term might be neglected.

There are also limitations to the reality of this research's simulation model, due to lack of substantial data on parameters such as the female percentage at different scales, actual environmental carrying capacity of Beijing, and the age-class-specific month mortality rates when population equals to the carrying capacity. These parameters are instead assumed in the model, which may lead to uncertainty in the results of this research. Moreover, parameters of age-specific mortalities, breeding capacity, and seasonality of reproduction were formulated based on results of field studies outside Beijing, so that they may experience local variations when applied to the city's feral cat management.

Additionally, the model of this research assumes isolation to the simulated park population, which may not be entirely reflected in reality. Although presumably much less significant than when a park is surrounded with community populations, feral cats in different isolated parks may still experience a certain level of interaction through long-distanced migration of dispersing individuals.

This study relies on population control to restrict the range that a feral cat population occupies. However, alteration in population structure that TNR induces or potential immigration might lead to displacement of cat territorial behavior, and cause deficiency or excess of population control to enhance territorial restriction. Future research might focus on:

1. The dependence of TNR efficacy on whether a TNR program is performed only once or is repeated at a certain time of a year, and its impact on the effect on timing and age classes;
2. Whether TNR success is nearly proportional to neutering rate, and variation in the effect of timing and target age class on TNR programs with different neutering rate;
3. Exploring conditions influencing TNR success in longer terms by constructing simulation models with shorter cycles and reducing error accumulation.
4. Deepening understanding of the dispersal of feral cats and the territorial effect of immigration members, and integrating such factors into the interactions between isolated park populations and their management.
5. Enrich comprehension of how feral cats utilize land, the correlation between population size and area occupation, and how this might be altered.

Furthermore, future research should concentrate on a smaller, local scale, and delve deeper into the living conditions and characteristics of local feral cat populations and controlling efforts, gaining more substantial data on local conditions of feral cat management.

For further comprehension of the effect of TNR timing and target age class addressed in this research, future simulations may also focus on the population dynamics of each age classes and the changes in the population structure through time.

Notably, the success of TNR programs may be impacted by non-TNR-induced living and reproduction conditions, such as changes in mortalities or breeding capacity through other environmental pathways. Future studies may consider exploring the effect of such factors to enhance predictable feral cat management. The cats' behavioral response to neutering could also influence the success of TNR programs, and may also be a focus of future studies.

Closing thoughts

While ambitious youths all over the world contribute their enthusiasm to animal management and conservation, rational decisions based on scientific research must not be neglected. Although it is most encouraging to see students hanging up posters and organizing feral cat neutering programs, without careful analysis and planning, all the youthful passion and public resource might be wasted, for instance, on a TNR program in the wrong season and on the wrong cats. Neither, however, is feral cat management a topic only to be explored in academic literature. The best of plans would become useless if no one bothers to implement them. Real actions must be taken in this brave excursion into a better co-existence with animals around us. And who could be better candidates for such actions than the new generation?

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