## **Short Communication**

**Adaptive management of an iconic invasive goat *Capra hircus* population**

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**Abstract**

We describe the first use of fertility control to manage a free-living mammal population in Europe. An immunocontraceptive vaccine (GonaCon) was used to reduce female fertility in an invasive feral goat *Capra hircus* population. Adaptive management was implemented to assess the feasibility of fertility control and to allow prediction of the required level of vaccination to limit goat numbers. The individual probability of breeding success decreased for two years following treatment. Understanding the population demographics alongside modelling of the individual and population-level responses to the vaccine are important for future management.

**Key words**: conflict management, feral goat, fertility control, GonaCon, immunocontraception, North Wales, population modelling.

**Running head:** Adaptive management of an invasive goat population

**Introduction**

Feral goat *Capra hircus* populations exist outside their original geographic range in many locations around the world (Hess et al. 2018). As an invasive species, feral goats can have major negative impacts, particularly on island ecosystems (Coblentz 1978). They are often the target of management actions, principally culling, sometimes with eradication as the ambition (Parkes 1990). However, killing large mammals is contentious and increasingly faces opposition from the public. Fertility control is an alternative approach to limit population size and can be used in resolving conflicts associated with the negative impacts of invasive species (Fagerstone et al. 2010, Massei & Cowan 2014).

A number of novel contraceptive technologies for wildlife have emerged in recent years, including an immunocontraceptive vaccine known as GonaCon that targets gonadotropin*-*releasing hormone(GnRH).GonaCon has been shown to be an effective single-dose vaccine in several species (reviewed by Hobbs & Hinds 2018); it has been shown to reduce female fertility for several years, although the effect can wane with time (Killian et al. 2006, Miller et al. 2008, Gionfriddo et al. 2011, Massei et al. 2012).

A population of feral ‘Kashmiri’ goats has existed on the Great Orme in North Wales for over 100 years. Their presence has become iconic to the landscape, but the population has the potential to become overabundant with negative impacts on the Special Area of Conservation and Site of Special Scientific Interest, as well as increasing conflicts with non-touristic local human interests. A partnership led by Conwy County Borough Council took on management of the herd in 2001, by which time the population had become a significant local visitor attraction. Culling was not a publicly acceptable management tool so alternative population management methods were needed. Some individuals were translocated individuals and silastic contraceptive implants were trailled in an unknown number of females which resulted in some population decline but was poorly documented. The use of GonaCon was implemented in 2009 with the aim of stabilising the population at around 120 animals.

Adaptive management, incorporating iterative monitoring and refinement of management (Williams 2011), was necessary as the effectiveness of the immunocontraceptive vaccine on individual breeding success was uncertain and therefore the required number of females to vaccinate in any one year had to be estimated and revised using population modelling.

We describe the adaptive management process used to refine model population parameters, in order to improve understanding of the population dynamics and inform future management strategies.

**Methods**

**Adaptive management study**

The target number of females to vaccinate was initially based on the suggestion by Hobbs et al. (2000) that in ungulate populations with high adult survival, >60% of females would need to be maintained as infertile to achieve a reduction in population size.

Biannual counts of the goat population from 1996 – 2018 were used to monitor the overall population trends and further herding, capture and monitoring details are in Appendix S1.

In 2009, 65 females were vaccinated and 15 were tagged controls. Study animals were ear-tagged to enable visual individual recognition. Age was estimated by counting the number of horn growth rings (Bullock & Pickering 1984, Dunbar et al. 1990). Treatment animals were vaccinated with a 1 ml dose of GonaCon, containing 1000 ug GnRH-mollusk-hemocyanin conjugate per ml, by injection in the upper left hind leg. Control animals were injected with a sham vaccination of 1 ml of saline solution. A blood sample was obtained from the jugular vein of each female to analyse the anti-GnRH antibody titres.

To monitor the effectiveness of the vaccine, a breeding census was undertaken each spring from 2010, recording the presence of females and the number with juveniles (kids) at heel. All tagged individuals were identified.

Animals were recaptured in June 2010 to obtain blood samples in order to reassess the anti-GnRH antibody titres. Four animals that had kids at heel were revaccinated.

At this point, census data of tagged females were used to parameterise a population model with the aim of refining the target percentage of the female population to be vaccinated in relation to anticipated population-level effects (Mair 2010). Productivity and survival parameters were based on the literature (Rudge & Smit 1970, Forsyth et al. 2003) and included an estimate of a 90% reduction in fertility for three years in vaccinated females. The model indicated that vaccination of 75% of adult females would reduce population growth rate to close to zero.

Based on the estimated total population size in June 2011, a further herding exercise was conducted with the aim to vaccinate or revaccinate 65 animals. As the vaccine effect was assumed to be reduced after three years, 70 animals were vaccinated in 2014.

**Modelling the effectiveness of GonaCon**

A generalised linear mixed-effects model was used to assess the effectiveness of the GonaCon vaccination by assessing variation in the annual breeding outcome for all tagged adult female goats (N=104). Breeding success was modelled as a logistic response in the lme4 package (Bates et al. 2015) in R version 3.4.2 (R Core Team 2018). The best model included a random effect for individual goat to account for intra-subject correlation and the fixed effects of age and treatment history (a set of three binary variables indicating whether the last treatment was within one, two, or three years).

The study population was under constant management, and the number of animals translocated varied each year, hence direct observation of the natural growth rate was not possible. Age-structured data of the tagged female population were assumed to be representative of the total population. The population dynamics were modelled using a state-space model within a Bayesian framework, using JAGS software, to allow flexibility in representing both the observation and process errors (Kéry & Schaub 2012). Productivity was modelled using the total number of females of each age class and an estimate of their fertility; priors were based on the values used by Mair (2010). The estimated treatment effect from the breeding success model was included and varied with time since last treatment. Survival varied among each age class and these priors were formulated based on the same inferences as the 2010 model. The model included a detection probability that assumed between 80-100% of the population were counted in the census. The model was used to estimate the population from 2009-2022 and for two alternative scenarios: 1) assuming no treatment, and 2) assuming treatment in 2009, 2010 and 2011 but not in 2014.

**Results**

The biannual counts showed the Great Orme goat population had increased from 60 to 200 individuals between 1996 and 2001 (Fig. 1), but the reasons for this are unclear. During the period of the immunocontraception study (2009 onwards) the population declined to around 100 animals.

**Treatment effects on individual breeding success**

Monitoring of the 104 tagged females from 2010-2017 provided record of 60 successful breeding events (females seen with kids at heel) and 419 non-breeding events (no kids at heel). The model suggested that GonaCon treatment significantly reduced breeding success for two years (Fig. 2). Breeding success decreased with age, and treatment was most effective during the first year, was still effective in the second year, but had no impact in the third year (Table 1).

**Adaptive management**

Retrospective analysis showed that the percentage of females with active immunocontraception varied between years (Fig. 3). It was not possible to accurately estimate and subsequently vaccinate a target number of treatment animals, due to the uncertainty of the true population size, the unknown longevity of the vaccine and practicalities of capture. The age structure of the female population proved to be very important in determining the treatment’s impact on the total population. The population in 2009 included more animals aged 4 to 8 years than average and very few animals over 11 (Fig. 4). As this cohort aged, it influenced the impact of immunocontraception on the total population.

**Modelling population effects of treatment**

The model estimated the observed decline in female population between 2010-2017 and predicted that, without further treatment, the population was unlikely to exceed a total of 150 animals in the next two years (Fig. 5). Under scenario (1) using 2009 data without treatment, the model predicted a population increase. Under scenario (2) assuming no treatment in 2014, the model predicted a more stable population. The uncertainty around the model estimates was much greater where little was known about the population; the confidence intervals in scenario (1), where only one year of age structure information was modelled, were almost double those where the population was monitored for nine years (Table 2).

**Discussion**

We demonstrate the value of using an adaptive management framework to assess the effectiveness of an immunocontraceptive vaccine to restrict population growth in a feral goat population. The population of feral goats on the Great Orme declined between 2009 and 2017 to within the target population, despite initial uncertainty about population growth rates and the longevity of the vaccine. Initial implementation of GonaCon was without full knowledge of how it would affect breeding success, and monitoring of the population was necessary to assess the impact on both individuals and the population as a whole to inform future management.

Adaptive management allowed the target number of females to be refined based on improved knowledge. Initial uncertainties were around the total population size, the fecundity and survival of individuals and how these changed with age. Monitoring and evaluation reduced uncertainty in the population models.

Previously vaccinated animals re-entering the breeding population is a further challenge in population management using immunocontraception (Hobbs & Hinds 2018). Monitoring the population allowed the impact of the vaccine on individuals to be quantified, which was important, as the number and age of animals with active vaccine varied through time. Therefore, knowledge of the age structure was important for modelling of the population dynamics in order to reduce uncertainty and refine plans for further vaccination. However, practical constraints limited the experimental design. For example it was unavoidable that there were too few known females unvaccinated to allow their productivity to be fully assessed, and capturing specific individuals for retreatment was constrained by time-frames and budget, so treatment was not always optimal.

This study, like other successful demographic regulation studies of animal populations, involved a small, closed population of readily accessible individuals (Ransom et al. 2014). While the potential of fertility control to offer safe, effective and humane approaches to wildlife management is beginning to be realised, it is important to acknowledge that it is not a universal panacea. Compared to culling, fertility control takes longer to achieve equivalent population reductions, simply because infertile animals remain in the population until they die (Hone 1992). Therefore, good knowledge of the population’s life history characteristics is essential for decision-making. We recommend the use of adaptive management to reduce uncertainty and improve the prediction of future management scenarios.

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Figure legends

Fig. 1. Abundance of the feral goat population at the Great Orme, North Wales, recorded as the sum of females, males and juveniles, between 1996 and 2017.

Fig. 2. Modelled estimated probability of breeding success with increasing age (in years) in the tagged female feral goat population. Treatment effects (number of years since last GonaCon treatment) are shown in different panels; data points from the same individual goat are joined by a line.

Fig. 3. Minimum percentage of female feral goats with active fertility treatment each year. For each year of contraception effect, the number of females considered to be under immunocontraception effect is compared against the highest number of females recorded in the previous year.

Fig. 4. Estimated abundance of female feral goats in different categories and per age (in years), from 2009-2017.

Fig. 5. Observed and estimated feral goat population abundance on the Great Orme, North Wales. Modelled estimates of the total population and female population for years 2009-2022, presented with 95% prediction confidence intervals (shaded bands) for all observed data, and under two alternative scenarios, assuming the last treatment was in 2011 and assuming no treatment. Census data for years 2009-2017 are plotted for females (points) and the total population (crosses).

SUPPORTING INFORMATION

Additional supporting information may be found in the online version of this article at the publisher’s website.

Appendix S1. Details of methods used for herding, capture and monitoring feral goats.

Table 1. Model coefficients of logistic generalised linear mixed model of breeding success in feral goats on Great Orme, North Wales.

|  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
|  | Odds ratio (OR) | OR lower 95% CI | OR upper 95% CI | Estimate | Standard error | z value | Pr(>|z|) | Estimate Lower 95% CI | Estimate Upper 95% CI |
| (Intercept) | 0.2015 | 0.0788 | 0.5154 | -1.6019 | 0.4791 | -3.3432 | 0.0008 | -2.5410 | -0.6628 |
| One year since last treated | 0.0885 | 0.0266 | 0.2939 | -2.4251 | 0.6125 | -3.9591 | 0.0001 | -3.6257 | -1.2245 |
| Two years since last treated | 0.2316 | 0.0798 | 0.6722 | -1.4628 | 0.5437 | -2.6905 | 0.0071 | -2.5285 | -0.3972 |
| Three years since last treated | 0.3190 | 0.0834 | 1.2200 | -1.1426 | 0.6844 | -1.6695 | 0.0950 | -2.4841 | 0.1988 |
| Age | 0.7225 | 0.6055 | 0.8620 | -0.3251 | 0.0901 | -3.6094 | 0.0003 | -0.5016 | -0.1486 |

Table 2. State-space model (SSM) estimates and confidence intervals for total feral goat population size in year n+2 beyond the data observations for the study, under two alternative scenarios: 1) assuming no treatment, and 2) assuming treatment in 2009, 2010 and 2011 but not in 2014.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
|   | Data duration (last year of data (n)) | Mean total population estimate for n+2 years  | Mean estimates for confidence interval (2.5%-97.5%) | Confidence Interval range  |
| SSM using all existing data | 9 years (2017) | 123 | 96 - 151 | 55 |
| SSM with no treatment in 2014 (scenario 2) | 6 years (2014) | 162 | 128-199 | 71.2 |
| SSM with no treatment (scenario 1) | 1 year (2009) | 233 | 188-281 | 108.8 |