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Estimating Key Largo woodrat (*Neotoma floridana smalli*) abundance using spatially-explicit capture recapture and trapping points transects

RH: Estimating Key Largo woodrat abundance

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ABSTRACT

The Key Largo woodrat (*Neotoma floridana smalli*) is an endangered rodent with a restricted geographic range and small population size. Establishing an efficient monitoring program of its abundance has been problematic, as previous trapping designs have not worked well because the species is sparsely distributed. We compared Key Largo woodrat abundance estimates obtained using trapping point transects (TPT) and spatially explicit capture-recapture (SECR) based on statistical properties, survey effort, practicality and cost. Both methods combine aspects of distance sampling with capture-recapture, but TPT relies on radio-tracking individuals to estimate detectability, and SECR relies on repeat capture information to estimate densities of home ranges. Abundance estimates using TPT in the spring of 2007 and 2008 were 333 woodrats (CV=0.46) and 696 (CV=0.43), respectively. Abundance estimates using SECR in the spring, summer and winter of 2007, were 97 (CV=0.31), 334 (CV=0.26), 433 (CV=0.20) animals, respectively. TPT used approximately 960 person-hours and 1,010 trap nights per season. SECR used approximately 500 person-hours and 6,468 trap nights per season. Significant time was saved in the SECR survey by setting large numbers of traps close together, minimizing time walking between traps. TPT was practical to implement in the field, and valuable auxiliary information on Key Largo woodrat behavior was obtained via radio collaring. In this particular study, detectability of the woodrat using TPT was very low and consequently the SECR method was more efficient. Due to large uncertainty in estimates, both methods require a substantial investment in survey effort to detect any change in abundance.

The Key Largo woodrat (*Neotoma floridana smalli*) is one of six recognized subspecies of the eastern woodrat (*Neotoma floridana*). It has a highly restricted geographic range, occupying extant, tropical hardwood hammock on northern Key Largo, Florida, USA. In 1984, the Key Largo woodrat was listed as a federally endangered subspecies, and is subject to a recovery plan that identifies potential threats and describes management actions to be undertaken (US DOI 1984; US FWS 1999). Management actions have included public land acquisition on north Key Largo, through the establishment of two wildlife reserves that have restricted public access; programs governing relocation, captive breeding and reintroduction for captive bred individuals (Alligood et al. 2008, 2009, FWC unpublished data); predator control (Muiznieks 2006), and enhancing habitat with supplemental nest structures (Winchester et al. 2009). A reliable population abundance estimate, together with an associated measure of uncertainty, is essential to evaluate the effectiveness of management actions and guide decision making for the Key Largo woodrat population.

Since the Key Largo woodrat is nocturnal, cryptic, and sparsely distributed, standard population monitoring methods do not work well (e.g., require unrealistic investment of survey effort; Winchester 2007). A review of potential methods to estimate Key Largo woodrat abundance conducted by Potts et al. (2006) concluded trapping point transects (TPT, Buckland et al. 2006, Potts et al. 2012) and spatially explicit capture-recapture (SECR, Borchers and Efford 2008, Royle and Young 2008) were two abundance estimation methods that warranted further investigation to assess whether either of these methods could realistically form the basis of a long-term monitoring program of Key Largo woodrat abundance.

Here, we compare abundance estimates for both methods based on statistical properties, survey effort, practicality and cost for data collected on the Key Largo woodrat. Due to practical limitations, the TPT and SECR surveys could not be undertaken simultaneously, nor is “true” abundance of the woodrat known. Potts et al. (2012) presented a detailed statistical analysis of TPT, and estimated yearly spring abundance of the woodrat between 2008 and 2011 using TPT. Here, we analyze an additional data set collected during a pilot study in 2007, and compare the 2007 and 2008 abundance estimates obtained using TPT with those from an SECR survey undertaken during spring, summer and winter of 2007.

STUDY AREA

Key Largo is the first island in the Florida Keys, linking the lower keys to the mainland. It is the largest island of the keys, covering approximately 21 km^2. Key Largo has an average elevation of 2.4 m above sea level and is formed from the exposed tops of ancient coral reefs (Hersh 1981). The climate of Key Largo is subtropical. Mean annual rainfall is approximately 102 cm (40 inches), with the majority of this precipitation occurring between June and October (US FWS 1999). Average maximum daily temperature in summer is approximately 29 degC (84 degF) decreasing to approximately 21 degC (70 degF) in winter (Gore and Loggins 2005).

Although tropical hardwood hammock was once the dominant vegetation type across Key Largo, due to urbanization, approximately only one third remains within two protected reserves that fall under different juradisticion: the Dagny Johnson Key Largo Hammock Botanical State Park, managed by the Florida Department of

Environment and Protection, and the Crocodile Lake National Wildlife Refuge, managed by the US Fish and Wildlife Service. Despite its protected status, the remaining tropical hardwood hammock is highly fragmented with roads, tracks, and abandoned developments.

The age and structure of the hardwood hammock is not homogeneous throughout Key Largo (Gore and Loggins 2005). Ross et al. (1992) and Ross et al. (1995) identified three strata delineated by age: young (disturbed since 1971, approx. 87 ha), medium (disturbed between 1940-71, approx. 327 ha), and old (disturbed before 1940, approx. 431 ha). A fourth stratum based urban areas located within the hammock (approx. 127 ha, representing approx. 13% of the total survey region) was omitted from this study since it was not considered suitable habitat.

METHODS

Spatially explicit capture-recapture (SECR)

SECR uses the known locations of the traps and the spatial pattern of recapture events to estimate the density of home range centers and a capture function (Borchers and Efford 2008, Royle and Young 2008). The capture function is conceptually consistent with a detection function in distance sampling, in that the probability of detecting an individual is assumed to be a radially decreasing function of the distance between the center of the animal's home range (unknown) and the distance to the trap (Buckland et al. 2001). Each animal has one home range center, and it follows that the density estimate of home range centers can be used to calculate abundance of all animals in the survey region.

Data collection.— Using a stratified random design with proportional allocation, 33 grids were established in the study area across three habitat strata (Fig. 1A). Sampling units were allocated in proportion to the area available in each habitat stratum.

Each of the 33 grids was trapped during the spring (March – May), summer (July – September) and winter (October – December) of 2007 for four consecutive nights. Each grid was a 7 by 7 array, with one single-catch Sherman trap placed at each trap station (i.e., 49 traps per grid) and 10 m spacing between traps (i.e., 19,404 trap nights in total). Traps were opened and baited with whole oats in the late afternoon and checked the following morning within the first two hours after sunrise. All captured woodrats were double-marked with passive integrated transponders (PIT) tags (AVID, Norco, California) and ear tags (#1005 Monel ear tags, National Band and Tag, Newport, Kentucky). Sex was recorded. Capture and handling was conducted under U.S. Fish and Wildlife endangered species permit Nos. TE139405-0, and TE137411-0, and, Florida Fish and Wildlife Conservation Commission Permit Nos. WV06293, Florida Department of Environmental Protection Division of Recreation and Parks Research and Collecting Permit Nos. 5-07-20, and 5-08-34, and University of Georgia Institutional Animal Care and Use Permit No. A2006-10206-m1.

*Capture probability model.—T*he capture probability model, $\boldsymbol{p_s}(\boldsymbol{d_k}(X))$, models the probability of detecting an animal at trap $\boldsymbol{k}$ on occasion $\boldsymbol{s}$, when the animal's true but unknown home range center is X (as defined by the coordinates of a point). Three forms of the capture probability model were considered: the half-normal, the exponential or the hazard rate. Following Efford et al. (2009), the form of the capture probability was first selected (i.e., null models were fitted whereby the parameters in the capture probability models were not dependent on any covariates). We used stepwise AIC to select a suitable model (but not necessarily the model with minimum AIC, Akaike 1973, Buckland, Burnham and Augustin 1997, Burnham and Anderson 2003). The covariates considered during model selection included time (as a factor, one level for each occasion), sex (as an individual level covariate), habitat (habitat strata was either young, medium or old), and two global behavioral trapping responses (learned, whereby there was a step change in the parameter after the first detection of an animal; or transient, where the parameter depended on detection at a previous occasion, i.e., a Markovian response).

Since the data were naturally sparse (i.e., few captures across the 33 grids, despite a large survey effort), “grid” could not be used as a covariate in the model, and consequently the probability of capture at distance zero (g0), and also the shape parameter (σ) was assumed equal across all grids. This assumption may not hold if the capture probability differs between grids (e.g., if there is a north-south gradient in capture probability with grid location, or changes with habitat type) and consequently the variability of abundance estimates might be biased low. A step-wise model selection procedure was used (rather than testing all combinations of covariates), as not all models could be fitted with all combinations of covariates, as the number of recapture events was small and this caused parameter identifiability issues (as observed when e.g., estimates of standard errors are unrealistically low – essentially zero – or unrealistically high).

*Estimating density of home range centers.—D*ensity $(\widehat{D})$ of home range centers was assumed to be distributed in space by a homogeneous Poisson process. $\widehat{D}$ was estimated using a Horvitz-Thompson-like estimator (Borchers and Efford 2008):

$$\widehat{D} = \sum_{i=1}^{n} \frac{1}{\hat{a}(\hat{\theta}, z_i)}$$

where $\hat{a}(\hat{\theta}, z_i)$ was the probability of detecting an animal *i* (for *i*= 1,…, n) given the parameters of the capture probability model defined in $\hat{\theta}$ (e.g., g0 and σ for a half-normal detection function) and a set of individual-based observed covariates z_i, regardless of its home range center (i.e., $\int p_{.}(X)\, dX$ where $p_{.}(X)$ is the probability of detecting an animal at least once in any trap). The integration of $\int p_{.}(X)\, dX$ was bound in space by specifying a habitat mask, that essentially defines a set of points in the survey region where an animal's home range center may be located. Without specifying a habitat mask, home range centers might be located in habitat known to be unsuitable causing density to be underestimated (Efford et al. 2009). A habitat mask was created using the boundary between known potential habitat (i.e., hammock) and non-habitat (i.e., surrounding mangrove swamp), available as an ESRI shapefile (http://www.esri.com/).

Density and variance were estimated by model-averaging across all fitted models proportional to AIC weight. All modeling was undertaken using the "secr" package (version 2.9.5, Efford 2010) in the statistical program R (v. 3.2.2, R Development Core Team 2010). Density (D) was then converted to abundance (N) using the area

(A) contained in the survey region (as defined by the habitat mask): N = D A.

In addition to the classic assumptions of standard capture-recapture (i.e., the population is closed within each of the 4-day secondary sampling occasions, each captured individual is uniquely marked and marks were not lost, or misread), SECR has the following additional assumptions (Borchers and Efford, 2008):

1. Animals occupy home ranges, and home-range centers are distributed within the masked habitat region following a Poisson-distribution, and
2. Animals are detected independently of each other.

Trapping point transects (TPT)

TPT requires two surveys (Buckland et al. 2006, Potts et al. 2012). Data collected during the *trial survey* are used to estimate a detection function, g(*r*) (i.e., the probability of catching an animal in a trap, given that the animal was at distance *r* from the trap, when the trap was set). The distance between the animal and the trap, when the trap was set might be known by visually locating the animal (e.g., Buckland et al. 2006) or via radio tracking (e.g., Potts et al. 2012). Then, for each animal detected during a separate *main survey*, its probability of detection can be predicted using the estimated detection function. A Horvitz-Thompson-like estimator (Borchers et al. 1998) can be used to estimate overall abundance. A TPT pilot survey was undertaken in spring 2007, and repeated yearly each spring between 2008 and 2011 (Potts et al. 2012). Here, we describe data collection for the 2007 and 2008 field seasons.

Main survey data collection.—The *main survey* comprised a randomly placed systematic grid of 137 sample points with 250 m trap spacing throughout potential habitat (Fig. 1B). Two traps were set at each trap location, following the same procedures as the SECR survey (i.e., opened in the afternoon using whole oat bait and checked the following morning), and trapped for three consecutive nights. All captured woodrats were double-marked with PIT (AVID, Norco, California) and ear tags (#1005 Monel ear tags, National Band and Tag, Newport, Kentucky). Sex was recorded. Trapping point transect fieldwork was permitted by the US Federal Fish and Wildlife Permit #TE139405-2, Florida Fish and Wildlife Conservation Commission #WV08573 and Florida Department of Environmental Protection #5-11-03.

Trial survey data collection.—Radio-transmitters were attached using a neck collar (mass < 10 g, AVM Instruments, California) to a subset of captured woodrats for the *trial survey*. Woodrats were selected to ensure equal sex representation in the sample and all weighed over >100 g (i.e., all were adults) to ensure collar weight did not exceed 10% of their body mass (as per permitting regulations). Each radio-collared woodrat was located at its nest daily (the trial start point), and two trial traps were set some random direction away from the trial start point. Typically, three trials were performed at each 5-m interval between 5 m and 60 m, but trial distances did extend beyond 60 m (up to 320 m) to ensure the tail of the distribution function was estimated accurately. Trial traps were checked the following morning to determine whether the radio-collared woodrat was captured at that trial distance, or not.

Estimating the detection function.—Using data collected during the trial survey, a detection function can be fitted using e.g. generalized linear mixed modeling (GLMM, Bates and Maechler 2009). The sample size of radio-collared woodrats in the trial survey conducted in 2007 and 2008 was not large enough to estimate the detection function reliably. And so the detection function used in this analysis was fitted to trial survey data pooled over 2008-2011 (see Supporting Information). The detection function assumed that the average probability of detection depended only on sex of the woodrat, distance of the trial animal from the trap when the trap was opened and a random effect about the intercept term. The ‘glmer’ function within the “lme4” package (v 1.1-7, Bates and Maechler 2009) in R (v 3.0.3, http://cran.r-project.org) was used to estimate the detection function.

Estimating abundance.—Abundance estimation followed using a Horvitz-Thompson-like estimator:

$$\hat{N} = \frac{A}{A_c}\sum_{i=1}^{n}\frac{1}{\int_0^w \pi_b(b)\hat{P}(b; z_{i1}, \dots, z_{iJ})db}$$

where A and A_c are the area of the survey region and covered region, respectively (note, A is the same area as specified by the habitat mask used for the SECR analysis); $\pi_b(b)$ is the probability density function of the random effects distribution; and $\hat{P}(b;\ z_{i1}, \dots,\ z_{iJ})$ is the estimated probability of detecting the *i*th animal captured in the main survey unconditional on its distance from the trapping sample point *r*. That is, $\hat{P}(b;\ z_{i1}, \dots,\ z_{iJ}) = \int_0^w \pi_r(r)\, p(r, b;\ z_{i1}, \dots, z_{iJ})dr$, where $\pi_r(r)$ is the probability density function of distances of individuals from the trapping sample point. A non-parametric bootstrap with $n = 999$ resamples was used to estimate the variance in abundance (Buckland et al. 2006, Potts et al. 2012).

It is assumed that the estimated detection function of animals in the trials survey is reflective of all animals in the main survey, and all sources of individual variation are included in the detection function.

Comparison of survey design-cost considerations

Survey effort (i.e., time spent), practicality and cost of data collected with both survey methods are compared and discussed.

RESULTS

Comparison of abundance estimation methods

In the SECR survey, capture rates were very low despite the large survey effort, ranging between 0.53 capture events per 100 trap nights in summer 2007 to 1.0 capture events per 100 trap nights in winter 2007. The number of total capture events in the hardwood hammock varied from 1.7 capture events per 100 trap nights in medium-aged hammock strata to 2.7 capture events per 100 trap nights in the old hammock strata (Table 1).

The capture model with the lowest AIC suggested g0 was dependent on sex of the woodrat, and σ was dependent on session. The model-averaged abundance estimates using SECR in the spring, summer and winter of 2007, were 97 (CV = 0.31), 334 (CV = 0.26), 433 (CV = 0.20) animals, respectively (Table 2). See Supporting Information for full model selection results.

In the main survey of the TPT method, in 2007 there were two female and four male woodrats captured three and six times, respectively, giving a capture rate of 1.1 capture event per 100 trap nights. In 2008, six female and eight male woodrats were captured six and 13 times, respectively, giving a capture rate of 2.3 capture events trap 100 trap nights. The detection probability of female and male woodrats, as estimated using a detection function fitted to NEW ANALYSIS 645 662 trial points collected on 34 35 female woodrats and 552 570 trial points collected on 23 24 male woodrats captured between 2008-2011, was very low (Fig. 2). The resulting estimates of woodrat abundance were 333 woodrats (CV = 0.46) and 696 (CV=0.43) in 2007 and 2008, respectively (Table 2).

Comparison of survey design-cost considerations

The uncertainty in abundance estimates using both methods was disappointingly large, despite the large investment in survey effort. In total, the TPT method required approximately 1,000 trap nights per field season, which equated to approximately 960 person-hours (a 4-person field team working full-time for approximately 8 weeks). The majority of this time was spent on the trials survey, and to obtain the detection function used here (Fig. 2), data were pooled across multiple years (2008-2011, Potts et al. 2012). It would be impractical to obtain a sample size sufficiently large within one field season to estimate the detection function used here, as woodrats are rarely captured, making it problematic to catch sufficient individuals to radio-collar in the trials survey (i.e., the trial survey was conducted on 59 individual animals between 2008-2011, and it is unlikely that 59 animals could be caught in one field season to allow sufficient trials).

Survey effort utilized in the SECR study was 6,468 trap nights each season, requiring approximately 720 person-hours (a 2-person field team working full-time for approximately 45 days). However, whilst undertaking this survey, all small mammals captured (including the Key Largo cotton mouse, *Peromyscus gossypinus allapaticola*) were processed. During 2007, there were approximately 1,700 small mammal captures, of which, Key Largo woodrat captures represented less than 10%. If the same survey design were to be undertaken focusing just on Key Largo woodrats, we estimate that it might take less than 500 hours per survey, since time would be saved by processing only the target species and not by-catch as well. Significant time-efficiencies for the SECR method, calculated per trap night (i.e., less person-hours required to check more traps) were gained by setting large numbers of traps close together, minimizing the time taken to walk between traps.

In both methods, traps can be set simultaneously. In the SECR method, approximately 3-4 grids were set simultaneously, requiring 196 unique traps. In contrast, TPT required approximately 60 unique traps (20 traps for the main survey and 10 trials, per night), so the initial out-lay for purchasing traps prior to commencing the survey was much less. Also, undertaking 6,468 trap nights in the SECR survey versus *c.* 1,000 trap nights in the TPT survey, required approximately six times as much bait to be purchased each survey season. However, the cost of bait for this project was small compared to the overall cost of each survey. These survey costs will vary when implementing these surveys for other species, but typically TPT will require substantially fewer traps than SECR.

DISCUSSION

Statistical estimation

In an ideal world, an experimenter would know the true abundance of a population, and use a variety of field methods and statistical techniques to estimate it (e.g., Parmenter et al. 2003 estimated abundance via complete removal within fenced enclosures). By knowing the survey effort of each field method, and the bias and precision associated with each abundance estimate, the experimenter can make an informed decision about which survey and statistical method provides the smallest variance and least biased estimate of the true population abundance. Although such studies are desirable, they are rare and perhaps impossible for many species and habitats, especially the Key Largo woodrat, with its cryptic nature and low detectability. By comparing population estimates obtained using data collected at around the same time, the risk that differences in population estimates from each method are attributable to population change is reduced.

Alternatively, simulation studies provide a means for investigating how different sampling strategies and levels of survey effort influence bias and variance in estimates of abundance (e.g., Potts et al. 2012). Potts et al. (2012) and Potts (2011) presented a simulation study for the trapping point transect survey, and found percentage bias in estimated abundance was low (*c.* 5%) with modest levels of survey effort (360 trap nights in the trial survey), but only if underlying average detection probability was high (probability of detecting an individual at distance zero was 0.8) and between-individual heterogeneity was low. Uncertainty and relative bias in population estimates increase with decreasing capture probabilities and increasing individual heterogeneity (i.e., between-individual variation). Field methods in the TPT survey (discussed below) could be changed to increase detectability of woodrats by e.g., changing bait type, or changing season in which the trapping survey occurs. In addition, we assume the estimated detection function is representative of all woodrats in the main survey and the estimated detection function models all sources of capture heterogeneity.

The simulation study conducted in Potts et al. (2012) found that detectability and between-individual variability comparable with this trapping point transect study concluded that bias was lowest (*c.* 7%) when at least 24 trials were conducted on each individual in the trial survey. Here, an average of 19 trials were conducted on 35 female woodrats and 24 trials on 24 male woodrats, between 2008 and 2011. Since the sample sizes used here are substantially smaller than required to have minimal bias, abundance estimates for the Key Largo woodrat obtained in this trapping point transect study may be biased high. Additionally, simulation studies presented in Potts (2011) and Potts et al. (2012) show that a tripling of effort in the main survey would reduce uncertainty by half.

In the spatially explicit capture-recapture analysis, we assumed that traps could capture more than one animal, but this is not true since single-catch Sherman traps were used in the field. Since single-catch traps are able to catch only one animal at a time, the capture probability is affected by the presence of other animals that may compete for traps. Capture of an animal disables a trap and immediately reduces the capture probabilities of neighboring animals. This assumption is clearly violated by the method of trapping used in the spatially explicit capture-recapture study, but any bias in estimated density is negligible unless trap saturation is very high (> 86%, Efford et al. 2009). Since the Key Largo woodrat population is at extremely low densities, levels of trap saturation at which density estimates will be biased are unlikely to be attained. In addition, every trap on the trapping grid will have between 2 and 4 adjacent traps within 10 meters, which would provide sufficient available traps to any individual woodrat. Examining by-catch for this study, during 2007 there were approximately 1,700 small mammal capture events across the entire survey year, but this was not problematic in terms of trap saturation, as it corresponds approximately to 9% of traps filled. Consequently, we assume that the effect of violating this assumption in the spatially explicit capture-recapture study is minimal.

There was a large discrepancy in estimated abundance in spring 2007, when both population estimation methods were applied simultaneously. Yearly-variation in the detection function was not taken into consideration in the trapping point transect survey as there were not enough data collected per year to determine this effect (i.e., the detection function reflects detectability of woodrats between 2008 and 2011, as estimated in Potts et al. 2012). Therefore, the abundance estimate in 2007 using the trapping point transect method might be biased. The discrepancy between estimates in the winter of 2007 using spatially explicit capture-recapture and the spring of 2008 using trapping point transect was also large; and the differences might simply reflect the large uncertainty in abundance estimates. Using other statistical models, for example open population spatially explicit capture-recapture models such as those developed by Gardner et al. (2010) may reduce uncertainty is abundance estimates.

Field design considerations

In the trapping point transect method, the large spacing (250 m) between trap locations in the main survey increased time to walk between locations to check traps. The benefit of this sparse array of traps was high survey coverage over the area of potential habitat. Consequently, areas of habitat were trapped that had not previously been surveyed. This sparse survey design also increased the encounter rate (i.e., number of captures per trap night) compared to any other study recently employed in the region. For example, McCleery (2003) and Winchester (2007) obtained capture rates of 0.11 and 0.29 woodrats per 100 trap nights, respectively, whereas the overall encounter rate using trapping point transect was 1.7 woodrats per 100 trap nights (i.e., 28 capture events across both years divided by 1,644 trap nights in the main survey), and for spatially explicit capture-recapture, it was 0.7 (i.e., 40 capture events across three seasons divided by 19,404 trap nights). Importantly, this does not imply that the woodrat population is increasing, just that efficiencies can be gained by differing survey design.

Extra time-efficiency might be gained by modifying trap configuration, for example by using hollow grids for the spatially explicit capture-recapture approach (Efford et al. 2005). However, hollow grids may reduce an already low encounter rate, and sparse data cause imprecise estimates (Efford et al. 2009). Alternatively, the spatial layout of the grid could be changed (e.g., McCleery 2003 and Winchester 2007 used 10 by 10 trapping grids with 25 m trap spacing), or more trapping grids could be placed in the survey area.

The most expensive aspect of the trapping point transect survey implemented in this study was the initial purchase of radio collars and the field time taken to locate radio-collared woodrats. Key Largo woodrats tend to nest below ground in rock-crevices, or in dumped rubbish including cars, washing machines and refrigerators. Such nesting-substrate attenuates the radio-tracking signal, increasing the time taken to locate individual woodrats (e.g., in some cases, it took 5 or more hours to locate a single woodrat). Should the trapping point transect method be applied to other species that nest in substrate that does not attenuate the radio-tracking signal, the time taken to locate individuals would be substantially less. In future research, it might be possible to avoid the radio-tracking component of the trial survey (leading to significant cost savings), by using the point-of-release as the trial start point (see Potts et al. 2012 and Potts 2011 for further discussion). This point-of-release approach could be viewed as a combination of trapping point transect and spatially explicit capture-recapture, in that the location of traps in the spatially explicit capture-recapture survey are moved each night, in response to where the animal was being captured (centered on its home range). This approach could be used for species that are too small to attach radio collars and should be investigated further.

One benefit of radio-collaring woodrats in the trapping point transect survey was gathering auxiliary information. Firstly, nest locations were identified and nesting behavior observed. Secondly, in our study we observed predation events by invasive species including Burmese pythons (*Python molurus bivittatus*, Greene et al. 2007) and feral cats.

With sufficient sample sizes and higher detectability, the trapping point transect approach can perform well with minimal bias in abundance estimates (Potts et al. 2012). When applied to the Key Largo woodrat, uncertainties were disappointingly large for the level of survey effort invested here. However, through radio tracking of individuals in the trial survey auxiliary information was obtained on movement, nesting locations and predator activity. The spatially explicit capture-recapture approach also had large uncertainty but was less than the trapping point transect and it did use fewer resources than the trapping point transect survey in terms of man-hours undertaken to complete the survey. Both monitoring approaches would require significant increases in survey effort to have any reasonable confidence of detecting further population declines of the Key Largo woodrat, or increases in abundance in response to management actions.

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FIGURE CAPTIONS

Figure 1. A) Map showing the SECR survey design. 33 trapping grids, each consisting for 49 traps laid in a 7 by 7 square with 10 m trap spacing where distributed in suitable habitat, defined by a "habitat mask" and shaded grey. B) Map showing the TPT main survey design. 137 survey points (each consisting of two traps) were distributed throughout the suitable habitat (shaded dark grey) based on a randomly-placed systematic grid with a 250 m trap spacing (black dots). Traps were not placed in unsuitable habitats of water (white) and mangrove swamp (light grey).

Figure 2. Probability of detection and 95% confidence intervals (shown as dashed lines) for female and male woodrats in the TPT trial survey.

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Figure 1A. and Figure 1B.

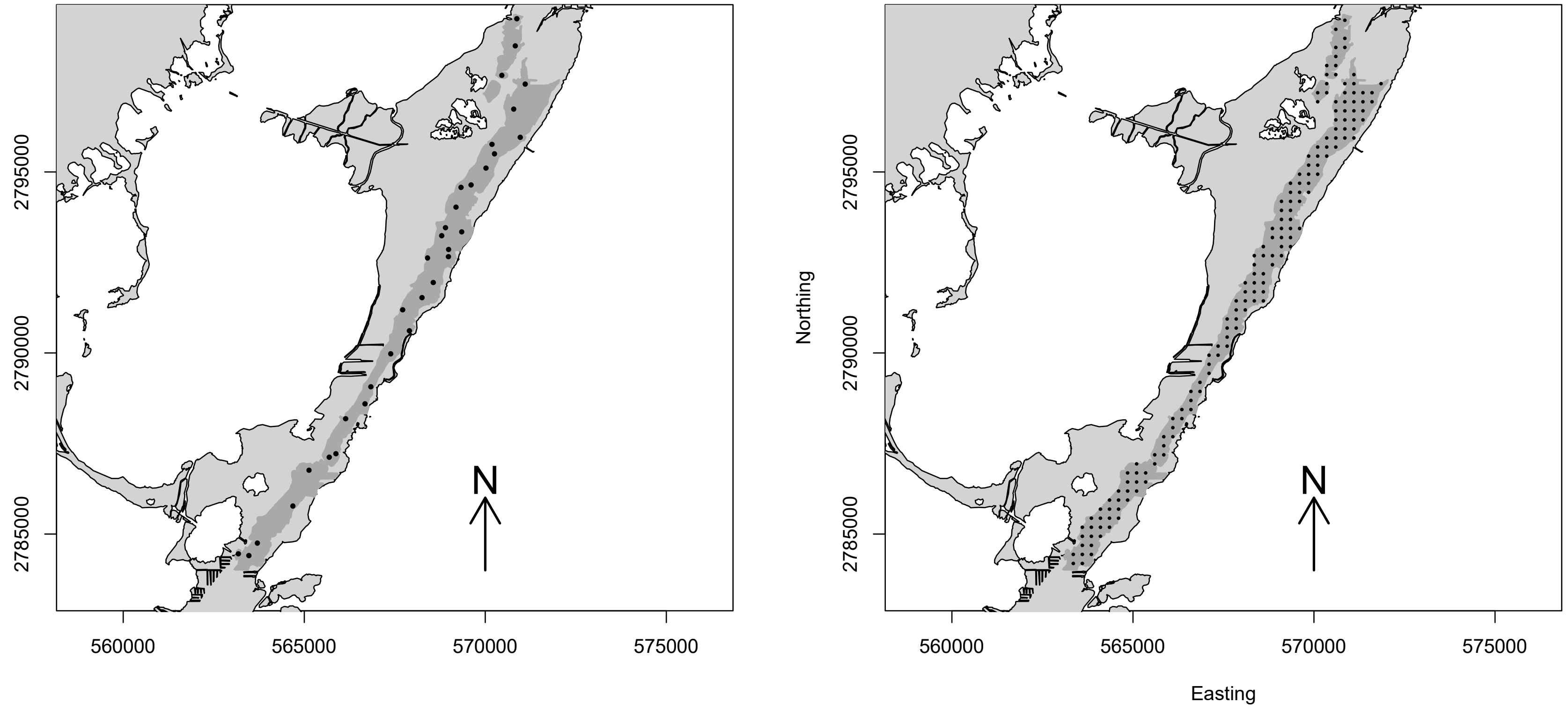
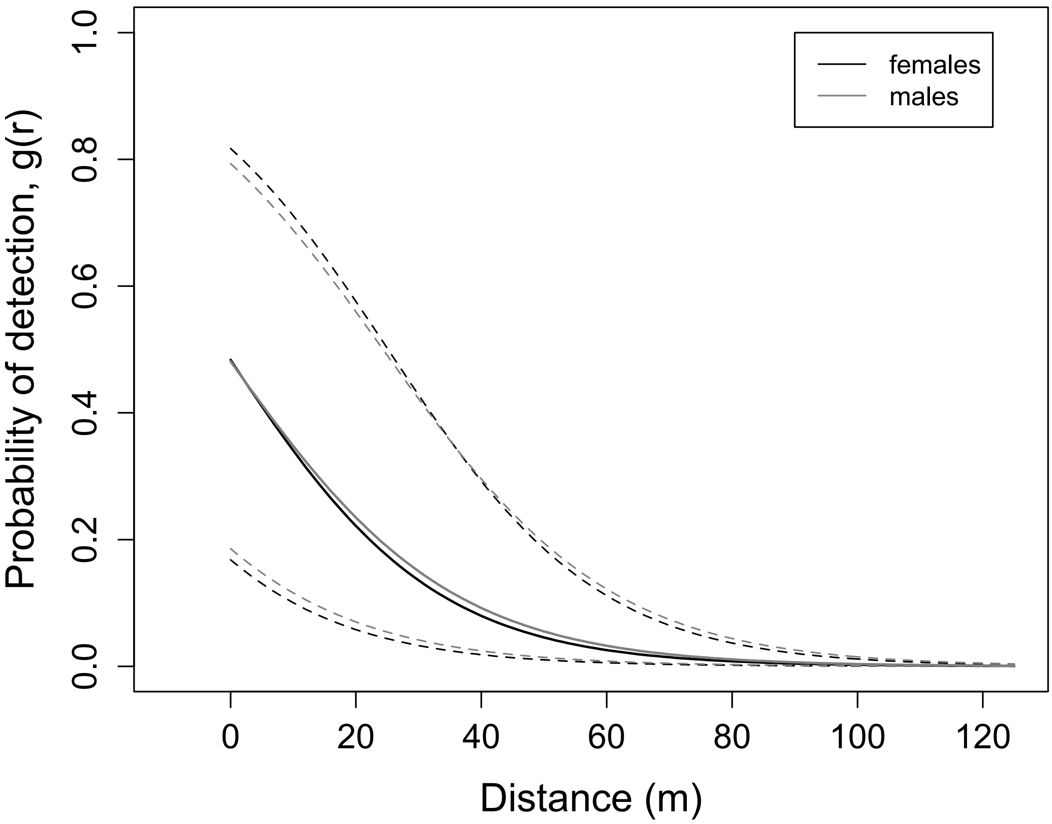


Figure 2.


females
males
Probability of detection, g(r)
0.0
0.2
0.4
0.6
0.8
1.0
0
20
40
60
80
100
120
Distance (m)

TABLES

Table 1. The number of woodrat capture events, with the number of unique woodrats captured given in parentheses, and the area of habitat (in hectares) for each of three habitat strata during the spatially explicit capture-recapture survey. A total of 33 grids were set for the 3 primary sessions (spring, summer, and winter). Row totals (i.e., by strata) for the number of woodrats caught are not a direct summation of each row, as some woodrats were caught across multiple sessions.

Hardwood hammock age stata	**Session**			**Total**	**No. grids**	**Area (ha)**
	Spring	**Summer**	**Winter**			
Old	26 (9)	16 (9)	45 (21)	87 (31)	16	431
Medium	10 (4)	14 (7)	16 (7)	40 (14)	12	327
Young	4 (2)	4 (2)	9 (4)	17 (6)	5	87
Total	40 (15)	34 (18)	70 (32)	144 (51)	33	845

Table 2. Estimated woodrat abundance using spatially explicit capture-recapture (SECR) and trapping point transects (TPT) during spring, summer and winter of 2007 and 2008.

Date	**Method**	**Estimate (CV)**
Spring 2007	TPT	333 (0.46)
Spring 2007	SECR	97 (0.31)
Summer 2007	SECR	334 (0.26)
Winter 2007	SECR	433 (0.20)
Spring 2008	TPT	696 (0.43)

SUPPORTING INFORMATION

Additional supporting information may be found in the online version of this article at the publisher’s web-site. Supporting information includes model selection results for the spatially explicit capture-recapture analysis, and capture information for individuals caught in the trapping point transect survey.

SUPPORTING INFORMATION

Appendix 1. The model selection results for the spatially explicit capture-recapture analysis.

Appendix 2. Capture information and analysis for individuals caught in the trapping point transect survey.

Appendix 1. AIC table of model selection results and derived abundance estimates. Capture data for the SECR analysis is available from the author upon request.

Table 1. Results of model selection for the SECR data.

model	detectfn	npar	logLik	AIC	AICc	dAICc	AICcwt
g0~sex sigma~session	halfnormal	5	-744.4703	1498.941	1499.958	0	0.7957
g0~1 sigma~session	halfnormal	4	-748.1528	1504.306	1504.972	5.014	0.0649
g0~1 sigma~session	halfnormal	4	-748.1838	1504.368	1505.034	5.076	0.0629
g0~B sigma~session	halfnormal	5	-747.1219	1504.244	1505.261	5.303	0.0561
g0~b sigma~session	halfnormal	5	-748.1354	1506.271	1507.288	7.33	0.0204
g0~t sigma~session	halfnormal	7	-747.4184	1508.837	1510.802	10.844	0
g0~session sigma~1	halfnormal	4	-754.3009	1516.602	1517.268	17.31	0
g0~1 sigma~sex	halfnormal	3	-758.2363	1522.473	1522.866	22.908	0
g0~B sigma~1	halfnormal	3	-758.796	1523.592	1523.986	24.028	0
g0~b sigma~1	halfnormal	3	-759.813	1525.626	1526.019	26.061	0
g0~sex sigma~1	halfnormal	3	-760.0062	1526.012	1526.406	26.448	0
g0~1 sigma~1	halfnormal	2	-761.1596	1526.319	1526.513	26.555	0
g0~1 sigma~b	halfnormal	3	-760.232	1526.464	1526.857	26.899	0
g0~1 sigma~B	halfnormal	3	-761.0796	1528.159	1528.553	28.595	0
g0~t sigma~1	halfnormal	5	-759.5687	1529.137	1530.154	30.196	0
g0~1 sigma~t	halfnormal	5	-760.9584	1531.917	1532.934	32.976	0

Table 2. Beta parameters of the model with the lowest AIC in Table S1 (g0~sex sigma~session).

	beta	SE.beta	lcl	ucl
g0	-0.9145916	0.3522817	-1.6050511	-0.2241321
g0.sex	-1.0659555	0.4085922	-1.8667815	-0.2651295
sigma	3.5809187	0.1269671	3.3320677	3.8297697
sigma.session2	-0.7492564	0.1403896	-1.024415	-0.4740977
sigma.session3	-0.4479637	0.1356239	-0.7137817	-0.1821458

```
> derived(gsex.ssession_norm)

# $`1`
       # estimate SE.estimate        lcl       ucl       CVn       CVa       CVD
# esa 130.3455489          NA         NA        NA        NA        NA        NA
# D     0.1150787  0.03615041 0.06307651 0.2099532 0.2581989 0.1789273 0.3141363

# $`2`
      # estimate SE.estimate       lcl       ucl       CVn        CVa       CVD
# esa 47.0267450          NA        NA        NA        NA         NA        NA
# D    0.3827609  0.09799164 0.2335923 0.6271864 0.2357023 0.09993458 0.2560126

# $`3`
      # estimate SE.estimate       lcl       ucl       CVn        CVa       CVD
# esa 61.6313606          NA        NA        NA        NA         NA        NA
# D    0.5192162   0.1023218 0.3541582 0.7612005 0.1777641 0.08506722 0.1970698
```

Appendix 2. Capture information from the TPT main survey conducted in 2007 and 2008.

Woodrat	Sex	Year_capt	MainSurveyPoint
3603	f	2007	31
3643	f	2007	107
3643	f	2007	107
3274	f	2008	32
3297	f	2008	36
3593	f	2008	87
3803	f	2008	79
3960	f	2008	14
3961	f	2008	8
4729	m	2007	5
3635	m	2007	15
3635	m	2007	15
3646	m	2007	31
3646	m	2007	31
3634	m	2007	69
3625	m	2008	93
3832	m	2008	59
3832	m	2008	59
3912	m	2008	93
3912	m	2008	93

3927	m	2008	93
3927	m	2008	93
3935	m	2008	80
3938	m	2008	78
3962	m	2008	16
3963	m	2008	15
3963	m	2008	15
3963	m	2008	15

Capture information from the TPT trials survey conducted in 2008-2011. Trials data for the TPT analysis collected between 2008-2011 is available from the author upon request.

Full estimation details of the detection functions are provided by Potts (2011) and Potts et al. (2012). A brief description is provided here. Trials data were centered by the group mean (i.e., on individual), and then the ‘glmer’ function within the lme4 (v 1.1-7) package was used in R (v 3.0.3):

```
glmer(Capture~Est_distC + Est_distN -1 + (1|Woodrat),
family=binomial("logit"), data=dat_all_years, nAGQ=5)
```

where Est_DistC was the average trial distance for each woodrat (i.e., group center), Est_distN was the distance between the group center and each trial, Woodrat was the identifier for each individual woodrat in the trials survey.