

## Articles

# Demography of the San Francisco Gartersnake in Coastal San Mateo County, California

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## Abstract

The San Francisco gartersnake *Thamnophis sirtalis tetrataenia* has been federally listed as endangered since 1967, but little demographic information exists for this species. We examined the demography of a San Francisco gartersnake population on approximately 213 ha of California coastal prairie in San Mateo County, California, from 2007 to 2010. The best-supported mark-recapture model indicated annual variation in daily capture probabilities and annual survival rates. Abundance increased throughout the study period, with a mean total population from 2008 to 2010 of 443 (95% CI = 313–646) individuals. Annual survival was slightly greater than that of most other gartersnakes, with an annual probability of survival of 0.78 (0.55–0.95) in 2008–2009 and 0.75 (0.49–0.93) in 2009–2010. Mean annual per capita recruitment rates were 0.73 (0.02–2.50) in 2008–2009 and 0.47 (0.02–1.42) in 2009–2010. From 2008 to 2010, the probability of an increase in abundance at this site was 0.873, with an estimated increase of 115 (–82 to 326) individuals. The estimated population growth rate in 2008–2009 was 1.52 (0.73–3.29) and in 2009–2010 was 1.21 (0.70–2.17). Although this population is probably stable or increasing in the short term, long-term studies of the status of the San Francisco gartersnake at other sites are required to estimate population trends and to elucidate mechanisms that promote the recovery of this charismatic member of our native herpetofauna.

Keywords: abundance; Bayesian analysis; California; Jolly–Seber model; population trend; San Francisco gartersnake; snake; survival; *Thamnophis sirtalis tetrataenia*

Received: January 24, 2011; Accepted: April 5, 2011; Published Online Early: April 2011; Published: June 2011

Citation: Halstead BJ, Wylie GD, Amarello M, Smith JJ, Thompson ME, Routman EJ, Casazza ML. 2011. Demography of the San Francisco gartersnake in coastal San Mateo County, California. *Journal of Fish and Wildlife Management* 2(1):41–48; e1944-687X. doi:10.3996/012011-JFWM-009

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## Introduction

Basic demographic information, although vital for conservation, is often lacking for rare or difficult-to-sample species and populations. The San Francisco gartersnake *Thamnophis sirtalis tetrataenia* (Figure 1) has no demographic data published in the peer-reviewed literature, despite calls for research on the demography of the species (U.S. Fish and Wildlife Service [USFWS] 1985). The

San Francisco gartersnake is a subspecies of the broadly distributed common gartersnake *Thamnophis sirtalis* and is primarily associated with wetland and pond habitats with adjacent grassy uplands, where it forages upon small anurans and salamanders (USFWS 1985). The San Francisco gartersnake is restricted to the San Francisco peninsula (one of the most densely populated areas of North America) from just north of the San Francisco–San Mateo County line south to approximately the San Mateo–Santa





**Figure 1.** Female San Francisco gartersnake *Thamnophis sirtalis tetrataenia*. Image used with permission from photographer Sebastian Kennerknecht, [www.pumapix.com](http://www.pumapix.com).

Cruz County line. Because of its limited distribution and attractiveness to collectors, the San Francisco gartersnake was federally listed as endangered in 1967 pursuant to the U.S. Endangered Species Act as amended (USFWS 1967; ESA 1973) and by the state of California in 1971 (California Department of Fish and Game Commission 1971). Six significant populations of the San Francisco gartersnake exist, although additional populations might occur on private lands (USFWS 2006). The primary objectives of the Recovery Plan for the San Francisco Gartersnake (USFWS 1985) are based on establishing and protecting multiple populations of sufficient size and 1:1 sex ratios with a stable or increasing trend. Demographic information on population sizes, sex ratios, and trends is limited.

The objectives of our study were to provide estimates of abundance, survival, recruitment, sex ratio, and population growth rate of the San Francisco gartersnake at a protected site in coastal San Mateo County, California. The results of our study are the first estimates of these demographic parameters for the San Francisco gartersnake in the peer-reviewed literature and provide information to help conserve this endangered species.

## Methods

Because the San Francisco gartersnake is under threat by collectors, we did not disclose details of the location or ownership of our study site. We conducted our study

on approximately 213 ha of former pasture in San Mateo County that was grazed by cattle for at least 100 y until 1998. The site consists of several wetlands and ponds constructed as cattle watering ponds, and uplands at the site are primarily grassland with varying degrees of shrub cover. Some upland forests also occur at the site. The site is occasionally managed with prescribed fire (burns in the study area occurred in 2005, 2006, and after our sampling in 2010) to reduce shrub encroachment and enhance the site's value for wildlife, including the San Francisco gartersnake.

We sampled the San Francisco gartersnake by using several different methods. Our primary method was drift fence and funnel trap arrays. In June 2007, we installed 24 drift fences (30 cm tall by 15 m long) constructed of 3.2-mm Masonite strips placed on edge. We located trap arrays at random locations, stratified by habitat, within 3–215 m (mean = 60 m) of wetlands, stock ponds, or reservoirs. We checked traps twice daily while open, and we used moistened sponges and shade covers to avoid desiccation or thermal stress of captured individuals. We placed two funnel traps constructed of 3.2-mm hardware cloth secured around a wooden frame on both ends of the drift fence, one on each side, for a total of four traps per array. When not in use, we closed traps by plugging the opening with a 5.1-cm Styrofoam ball secured by a small nail pierced through the hardware cloth. Trapping dates were sporadic in 2007 because of permitting,

construction of traps, and protocol development. In 2008, we used a 10-d open, 14-d closed schedule from late March to early June. To assess the efficiency of sampling at different times throughout the active season, we used a 10-d open, 20-d closed schedule from April 2009 to August 2009. In 2010, traps were open daily from late April to late June. Trapping in 2010 was delayed by a wet winter and site conditions that did not permit deploying traps earlier in the year.

We also captured the San Francisco gartersnake by using cover objects, standardized visual surveys, and opportunistic observations. We intensively checked cover objects that naturally occurred in the environment and those that were intentionally placed in 2007. We reduced the intensity of cover object searches in subsequent years as we increased our trapping effort. Cover objects were plywood or corrugated tin and ranged from  $65 \times 82.5$  to  $65 \times 121$  cm (mean area =  $0.69 \text{ m}^2$ ) for plywood and from  $70 \times 76$  cm to  $70 \times 92$  cm (mean area =  $0.60 \text{ m}^2$ ) for tin. Standardized visual surveys were conducted from March to May 2009 by slowly walking designated sections of the shorelines of cattle ponds, wetlands, and reservoirs while searching for snakes. In addition to standardized surveys, we recorded data on snakes that were captured incidentally. In total, we surveyed the site 26 d (7 d of which included trapping for 66 array-days) before 1 July in 2007, 43 d (40 d of trapping for 960 array-days) in 2008, 40 d (29 d of trapping for 666 array-days) in 2009, and 57 days (56 d of trapping for 1,320 array-days) in 2010.

Regardless of the method of capture, all captured individuals were processed in batches. We transported captured individuals in cotton sacks to a temporary field station where they were maintained overnight in climate-controlled chambers to prevent thermal stress until they could be processed the next day. We measured (snout-vent length [SVL], tail length, and mass), sexed, uniquely marked (passive integrated transponder tag or unique microbrand [Winne et al. 2006]), and photographed each individual. We released all individuals at their location of capture as soon as possible after processing.

We described the sex ratio, size, and sexual size dimorphism of the San Francisco gartersnake by using Bayesian analysis of binomial proportions and *t*-tests with unequal variances (Kéry 2010). We used the first capture of each individual for analysis. We eliminated gravid females from the analysis of sexual size dimorphism in mass. We used uninformative priors for each model, which were  $\text{Be}(1,1)$  for the binomial probability of a captured snake being male,  $\text{U}(0, \text{maximum of SVL or mass})$  for the mean of SVL and mass, and  $\text{U}(0,1000)$  for the standard deviation of SVL and mass. For sexual size dimorphism, we compared posterior support of models assuming a normal distribution and a lognormal distribution with the deviance information criterion (Spiegelhalter et al. 2002). We analyzed each model using Markov chain Monte Carlo methods as implemented in WinBUGS 1.4.3 (Lunn et al. 2000) with three chains of 10,000 iterations each, thinned by a factor of 3 after 1,000 burn-in iterations. We selected starting values for

each chain that were dispersed throughout the prior density for each parameter. We examined history plots and the Gelman–Rubin statistic (Gelman et al. 2004) as calculated by package coda (Plummer et al. 2008) for each parameter for evidence of lack of convergence. We did not find any indication of lack of convergence, and chains seemed well mixed.

We examined the abundance, apparent survival, and recruitment of the San Francisco gartersnake by using open population capture–recapture models. We only used data collected from March to June 2008–2010 (only four individuals were captured before 1 July in 2007, and these individuals were not recaptured before 1 July in subsequent years) to avoid within-season recruitment of neonates (which are primarily born in July and August [USGS, unpublished data]) and to better meet assumptions of instantaneous within-season sampling. We used a Bayesian analysis of the Schwarz–Arnason superpopulation formulation of the Jolly–Seber model (Royle and Dorazio 2008). This approach augments individual capture histories with a large number of all-zero capture histories of pseudoindividuals that represent a mixture of individuals that were part of the population and never captured and those that were not part of the population. This model is similar to a dynamic occupancy model, except that in capture–recapture studies the all-zero detection histories are never observed and death is an absorbing state (unlike sites, which can be recolonized after extinction). We examined the support for four different models,  $p \cdot \gamma_t \Phi$ ,  $p_t \gamma_t \Phi$ ,  $p \cdot \gamma_t \Phi_t$ , and  $p_t \gamma_t \Phi_t$ , where  $p$  is daily capture probability,  $\gamma$  is the probability that an individual member of the population is recruited into the population,  $\Phi$  is the apparent survival probability (apparent because mortality and temporary emigration are confounded in the model), and the subscripts  $\bullet$  and  $t$  denote constant and time-varying model parameters, respectively. Note that all models assume constant daily capture probabilities within a year, but models  $p_t$  allow daily capture probability to vary among years. Although we collected data under the robust design (Pollock 1982), daily capture probabilities were extremely low and very few individuals were recaptured within a season. We therefore did not estimate temporary emigration (Kendall et al. 1995). Instead, we used the robust design to eliminate confounding between  $p$  and  $\Phi$  at the final annual sampling occasion and interval (Royle and Dorazio 2008). Low daily capture probabilities also prevented the evaluation of individual covariates, which must be imputed for individuals that were not captured in each season, upon capture and survival probabilities. Bayesian analysis of closed population models by using data augmentation (Royle and Dorazio 2008) for 2010 (the only season for which fitting these models with uninformative priors was possible) indicated that constant daily capture probabilities had greater posterior support than time-varying capture probabilities or capture probabilities varying by sex or SVL (USGS, unpublished data).

We evaluated the models under two sets of priors. The first set of priors was selected to be uninformative. In this case, we set priors on  $p$ ,  $\Phi$ , and  $\psi$  (the inclusion

probability; Royle and Dorazio 2008) to be  $U(0,1)$ . We set the prior for entrance probabilities ( $\gamma$ ) equal for all four sampling periods with a Dirichlet(1,1,1,1) prior, with implementation as parameterized in Royle and Dorazio (2008). The second set of priors used personal experience to elicit priors for  $p$ , and values from the literature to set the prior distribution for  $\Phi$ . For  $p$ , we were confident (based upon prior experience sampling gartersnakes by several different methods) that daily capture probabilities for individuals would be less than 0.1 and therefore used a  $Be(1,35)$  prior, which has median = 0.020 and 2.5 and 97.5% quantiles of  $8.4 \times 10^{-4}$  and 0.100. For  $\Phi$ , we used values for *T. sirtalis* and other *Thamnophis* species from the literature (Larsen and Gregory 1989 [red-sided gartersnake *Thamnophis sirtalis parietalis*]; Bronikowski and Arnold 1999 [terrestrial gartersnake *Thamnophis elegans*]; Stanford and King 2004 [plains gartersnake *Thamnophis radix*]; Lind et al. 2005 [aquatic gartersnake *Thamnophis atratus*]), for which the minimum and maximum values of confidence limits were 0.21 and 0.90. We therefore used a  $Be(4,3)$  prior, which has median = 0.579 (2.5 and 97.5% quantiles = 0.223 and 0.882). We maintained uninformative priors for  $\psi$  and  $\gamma$ , for which we did not have prior information. In addition to daily capture probabilities and annual survival probabilities, we calculated the following derived parameters: annual abundance,  $N_t$ ; the number of snakes at the site during the entire study,  $N_{super}$ ; annual recruitment (the number of individuals born in year  $t - 1$  and surviving until year  $t$ , plus immigrants between year  $t - 1$  and year  $t$ ),  $B_t$ , from which we calculated annual per capita recruitment rates as  $B_t/N_{t-1}$ ; and the population growth rate,  $\lambda_t$ , calculated as  $N_{t+1}/N_t$  (Supplemental Material, Text S1; <http://dx.doi.org/10.3996/012011-JFWM-009.S1>). For each model, we augmented the number of observed individuals with 1,000 pseudoindividuals (Royle and Dorazio 2008). We determined that augmentation of 1,000 individuals was sufficient by examining the posterior distribution of  $\psi$  to ensure that it was distant from 1, and of  $N_{super}$  for a lack of mass at and above 1,000 individuals. We evaluated evidence for an increase in abundance at the site between 2008 and 2010 by subtracting the 2008 abundance estimate from the 2010 abundance estimate at each iteration of the Markov chain Monte Carlo algorithm, and calculating the proportion of positive differences. We repeated a similar procedure to evaluate evidence for a greater than 10% decrease or increase. We analyzed all models using Markov chain Monte Carlo methods as implemented in WinBUGS 1.4.3 (Lunn et al. 2000) with five chains of 25,000 iterations each, thinned by a factor of 5 after 5,000 burn-in iterations. We selected starting values for each chain that were dispersed throughout the prior density for each parameter. We examined history plots and the Gelman–Rubin statistic (Gelman et al. 2004) as calculated by package coda (Plummer et al. 2008) for each parameter for evidence of lack of convergence. We determined the adequacy of each model with a posterior predictive model check using a Bayesian  $P$ -value (Kéry 2010; Link and Barker 2010). We compared posterior support for different models using deviance information

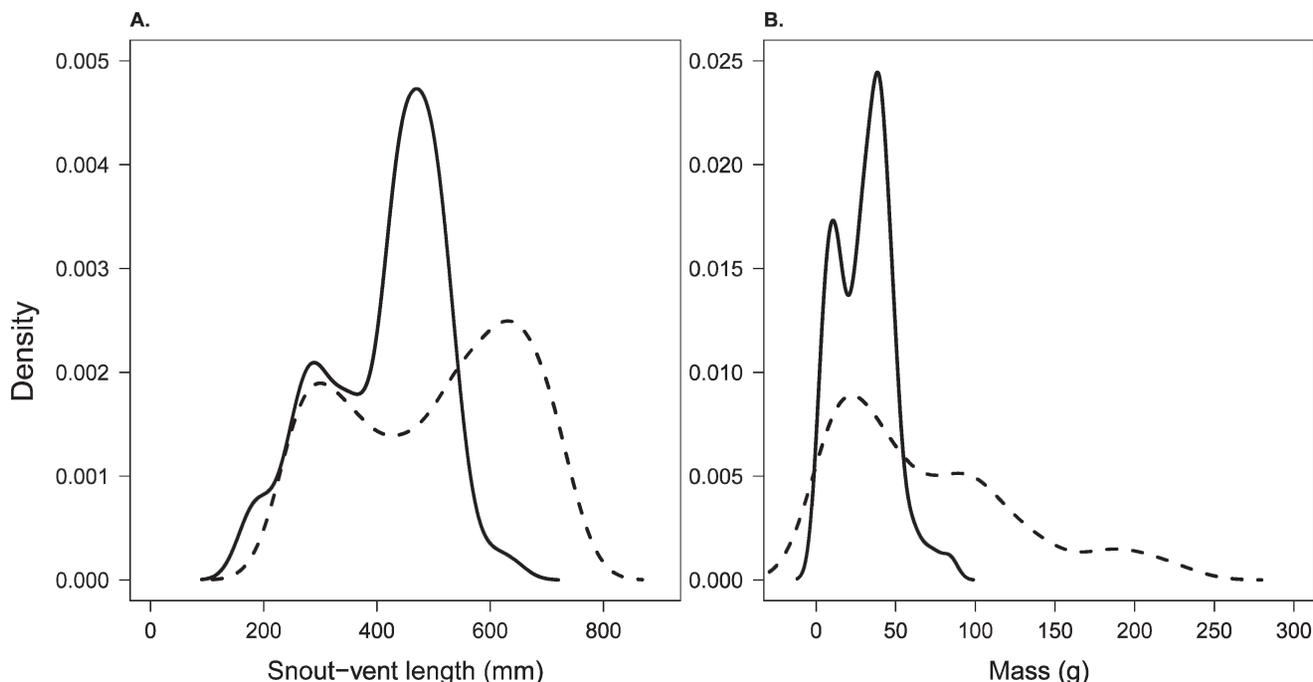
criterion (Spiegelhalter et al. 2002). For all parameters, we represent posterior distributions with the mean and 95% symmetrical credible interval ([CI], i.e., the 0.025 and 0.975 quantiles of the distribution).

## Results

Over the 4 y of our study, we captured 149 individual San Francisco gartersnakes 185 times (Supplemental Material, Table S1; <http://dx.doi.org/10.3996/012011-JFWM-009.S2>). Seventy-seven individuals were male, 66 were female, and 6 were of unknown sex, resulting in a sex ratio of 1.16 (95% CI = 0.85–1.62). Normal distributions were best-supported for male and female SVL (change in deviance information criterion between normal and lognormal = 25.3), and lognormal distributions were best-supported for male and female mass (change in deviance information criterion between lognormal and normal = 17.0). This species is sexually dimorphic for both SVL (male mean = 416 mm [391–442]; female mean = 515 mm [476–554]; difference = 99 mm [53–145]; Figure 2) and mass (male mean = 24.4 g [20.0–29.6]; female mean = 39.6 g [28.6–53.6]; difference = 15.2 g [3.1–29.6]; Figure 2).

One-hundred twenty-two individuals were captured 148 times before 1 July in 2008–2010 for analysis of abundance, survival, and recruitment (Supplemental Material, Table S1; <http://dx.doi.org/10.3996/012011-JFWM-009.S2>). Sixteen individuals were captured before 1 July in more than 1 y, but only three were captured in all 3 y. Seven individuals were recaptured twice in the same season (two in 2008, one in 2009, and four in 2010). The best-supported Jolly–Seber model using uninformative priors was  $p_t\gamma_t\Phi_t$  (Table 1). No evidence for lack of convergence existed for any model, with the Gelman–Rubin statistic less than 1.02 for all monitored parameters under model  $p_t\gamma_t\Phi_t$ . Similarly, no evidence for lack of fit existed for model  $p_t\gamma_t\Phi_t$  (Bayesian  $P$ -value = 0.787). Daily capture probabilities were very low, with posterior support for all years indicating daily capture probabilities less than 0.01 (Table 2). Annual capture probabilities were 0.18 (0.08–0.33) in 2008, 0.15 (0.08–0.24) in 2009, and 0.19 (0.12–0.29) in 2010. Annual survival probability varied during the study, with a mean of 0.88 (0.63–1.00) in 2008–2009 and 0.82 (0.51–0.99) in 2009–2010. The mean annual per capita recruitment rate between 2008 and 2009 was 0.73 (0.02–2.58) and between 2009 and 2010 was 0.44 (0.02–1.36). Annual abundance increased throughout the study period (Table 2), with an estimated superpopulation of 427 (298–611) individuals at the site from 2008 through 2010 (Table 2). The difference between abundance in 2010 and abundance in 2008 was 147 (–43 to 360). The probability that the population was increasing was 0.880, and the probability that it was increasing by more than 10% annually was 0.832. Conversely, the probability that the population was decreasing by more than 10% annually was 0.018. The population growth rate was 1.61 (0.83–3.47) in 2008–2009 and 1.27 (0.69–2.24) in 2009–2010 (Table 2).

Accounting for prior knowledge based upon estimated survival rates in the literature and experience trapping



**Figure 2.** Kernel density plots of snout-vent length (A) and mass (B) for first captures of male (solid line) and female (dashed line) San Francisco gartersnakes *Thamnophis sirtalis tetrataenia* in coastal San Mateo County, California, 2007–2010. Gravid females were excluded from mass measurements (B); all captured individuals were otherwise included.

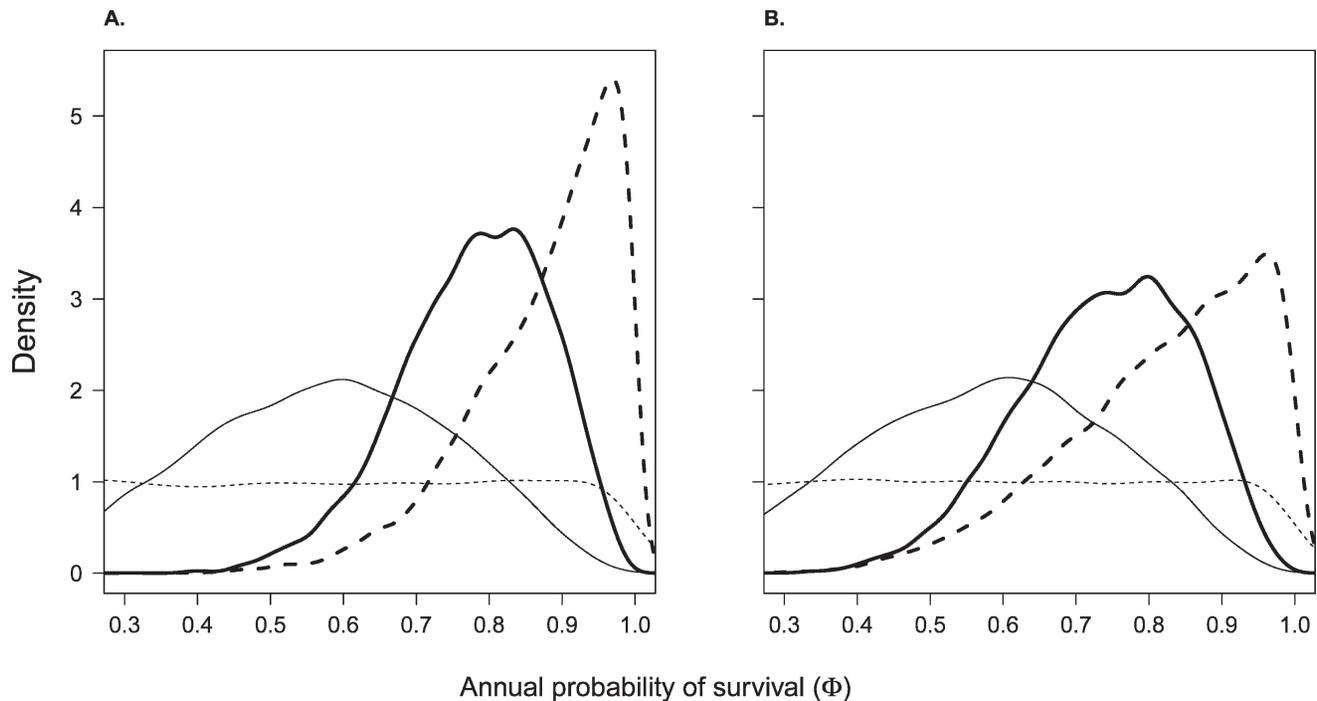
gartersnakes resulted in few changes to posterior inference (Table 1; Figure 3). Based upon deviance information criterion, the best-supported model under uninformative priors was still  $p_t\gamma_t\Phi_t$  (Table 1). No evidence for lack of convergence existed for any model, with the Gelman-Rubin statistic less than 1.05 for all monitored parameters under model  $p_t\gamma_t\Phi_t$ . Similarly, no evidence for lack of fit existed for model  $p_t\gamma_t\Phi_t$  (Bayesian  $P$ -value = 0.791). Informative priors had very little influence on daily or annual capture probabilities (Table 2) but did

**Table 1.** Model selection results under two different sets of priors for the Schwarz–Arnason parameterization of Jolly–Seber open population models for the San Francisco gartersnake *Thamnophis sirtalis tetrataenia* in coastal San Mateo County, California, from 2008 to 2010. Models are listed in order of decreasing support, where  $p$  represents daily capture probability,  $\gamma$  represents the annual probability of recruitment of an individual into the population, and  $\Phi$  represents the apparent annual probability of survival; subscripts  $t$  and  $\bullet$  represent annually varying and constant values of these parameters, respectively; DIC represents deviance information criterion and  $\Delta$ DIC represents change in deviance information criterion.

Model	Uninformative priors		Informative priors	
	DIC	$\Delta$ DIC	DIC	$\Delta$ DIC
$p_t\gamma_t\Phi_t$	2,242.0	0.0	2,258.9	0.0
$p_t\gamma_t\Phi_\bullet$	2,246.3	4.3	2,280.4	21.5
$p_\bullet\gamma_t\Phi_\bullet$	2,266.0	24.0	2,331.6	72.7
$p_\bullet\gamma_t\Phi_t$	2,416.4	174.4	2,498.5	239.6

**Table 2.** Posterior means and 95% symmetric credible intervals for parameters of interest under the best-supported Schwarz–Arnason parameterization of the Jolly–Seber model ( $p_t\gamma_t\Phi_t$ ) for abundance and survival of the San Francisco gartersnake *Thamnophis sirtalis tetrataenia* in coastal San Mateo County, California, from 2008 to 2010 with uninformative and informative priors, where  $p_t$  is the daily probability of capture in year  $t$ ,  $\Phi_t$  is the apparent annual survival probability in interval  $t$ ,  $B_t$  is the number of recruits (individuals born and surviving 1 y plus immigrants) in year  $t$ ,  $N_t$  is the abundance estimate in year  $t$ ,  $N_{super}$  is the total number of individuals that were ever a member of the population from 2008 to 2010, and  $\lambda_t$  is the population growth rate in interval  $t$ .

Parameter	Uninformative priors		Informative priors	
	Mean	95% CI	Mean	95% CI
$p_1$	0.005	0.002–0.009	0.004	0.002–0.009
$p_2$	0.004	0.002–0.007	0.004	0.002–0.007
$p_3$	0.004	0.002–0.006	0.004	0.002–0.006
$\Phi_1$	0.88	0.67–1.00	0.78	0.55–0.95
$\Phi_2$	0.82	0.55–0.99	0.74	0.49–0.93
$B_2$	113	6–293	119	6–297
$B_3$	112	7–282	114	8–288
$N_1$	202	91–364	210	94–394
$N_2$	290	170–452	284	164–450
$N_3$	349	221–531	325	209–502
$N_{super}$	427	298–611	443	313–646
$\lambda_1$	1.61	0.83–3.47	1.52	0.73–3.29
$\lambda_2$	1.27	0.69–2.24	1.21	0.70–2.17



**Figure 3.** Posterior distributions for annual survival probability of the San Francisco gartersnake *Thamnophis sirtalis tetrataenia* in coastal San Mateo County, California, 2008–2009 (A) and 2009–2010 (B). Dashed lines indicate uninformative prior (thin) and posterior (heavy) distributions, and solid lines indicate prior (thin) and posterior (heavy) distributions informed by experience and the published literature.

slightly reduce annual survival probability estimates to 0.78 (0.55–0.95) for 2008–2009 and 0.74 (0.49–0.93) for 2009–2010 (Figure 3). Abundance and recruitment estimates were affected very little by informative priors (Table 2). With informative priors, the difference between abundance in 2010 and abundance in 2008 was 115 (–82 to 326). The probability that the population was increasing was 0.873, and the probability that it was increasing by more than 10% annually was 0.740. Conversely, the probability that the population was decreasing by more than 10% annually was 0.038. The population growth rate based upon informative priors was slightly lower than that based upon uninformative priors, with 1.52 (0.73–3.29) in 2008–2009 and 1.21 (0.70–2.17) in 2009–2010 (Table 2).

### Discussion

Our study demonstrated that the San Francisco gartersnake population seems to be doing well at our study site, with high survival and increasing abundance. Despite the promising current status of this population, additional research at this and other sites is required to examine the long-term status of populations and mechanisms that promote high survival and recruitment resulting in positive population growth.

The increase in abundance could be caused by several mechanisms. The high survival rate promotes positive population growth, and this population might be in a growth phase with little intraspecific competition. The prescribed burns in 2005 and 2006 also might influence the growth of this population. Substantial direct

mortality from fire is uncommon in snakes (Russell et al. 1999; Smith et al. 2001; Webb and Shine 2008), although exceptions exist (Durbian 2006; Lyet et al. 2009). Prescribed fire could have the desired effect of increasing the suitability of the habitat for the San Francisco gartersnake or its amphibian prey, resulting in increased abundance over time. Additional research is required to examine the mechanisms responsible for positive population growth at this site and whether similar management practices will increase abundance of other populations.

The annual survival probability of San Francisco gartersnake is similar to or slightly higher than that of other gartersnakes. Annual survival of northern populations of the red-sided gartersnake varied annually, with point estimates ranging from 0.63 to 0.73 and 95% confidence limits ranging from 0.42 to 0.90 for years in which estimates were relatively precise (Larsen and Gregory 1989). Annual survival rates of the terrestrial gartersnake varied with habitat, with 95% confidence limits of adult survival ranging from 0.34 to 0.57 in lake populations and from 0.71 to 0.86 in mountain populations (Bronikowski and Arnold 1999). Survival rates of the plains gartersnake annual in Illinois varied with age and sex, with highest survival among 2-y-old females (0.52 [0.32–0.71]; Stanford and King 2004). A long-term study of the aquatic gartersnake in northern California demonstrated that survival rates of males and females differed, with females having greater survival rates (0.64 [0.60–0.68]; Lind et al. 2005). Ignoring prior information from these studies, the posterior modes

(which under uninformative priors are more comparable with maximum likelihood estimates than posterior means [Link and Barker 2010]) of annual survival of our study population were 0.97 in 2008–2009 and 0.96 in 2009–2010, although our credible intervals overlapped confidence limits of most other studied gartersnake populations. We suggest that incorporating information from previous studies to generate informative priors for analysis is a more profitable use of this information than post hoc comparisons.

The relatively high annual survival probability of the San Francisco gartersnake might be caused by a combination of high abundance of prey resources, limited human access to the site, and a relatively low incidence of predation. We have observed three mortalities on the site: two snakes were run over by vehicles, and one was found dead of unknown causes. The latter individual exhibited no external wounds and was completely intact, suggesting predation was not the cause of mortality. Identifying important sources of mortality for this species remains a key step toward promoting its recovery.

Although our study provides estimates of abundance for the San Francisco gartersnake, it cannot provide reliable estimates of density. It is difficult to determine the effective sampling area of trap arrays, and our small number of recaptures provides little information on the movements of this species. Increased sampling effort and the use of spatial capture–recapture models (Royle and Young 2008) would provide a robust method of estimating absolute densities for this species.

The recovery plan for the San Francisco gartersnake establishes as a goal 10 populations consisting of at least 200 adults in a 1:1 sex ratio (USFWS 1985), although the utility of the latter metric as a goal has been questioned (USFWS 2006). The probability that our population contained at least 200 individuals in 2010 was 0.99. If we assume (based upon the size distributions in Figure 2), that approximately two-thirds of the population consists of adult snakes, the probability that the abundance of adults is greater than 200 (corresponding to a total abundance of 300) is 0.58. In this population, the sex ratio was very near 1:1. Our multiple sampling methods may have minimized sex-based sampling biases, although fully accounting for sampling bias in capture probabilities (and other parameters) will require higher capture probabilities or increased sampling effort. Despite the limitations of our data, the simple calculation of derived parameters and intuitive interpretation of posterior distributions made the Bayesian paradigm well suited for evaluating the attainment of recovery objectives (Wade 2000). Remaining recovery objectives require the demonstration of long-term stability or growth at 10 populations (USFWS 1985), criteria that the current study is unable to address.

The Bayesian analysis of Jolly–Seber models using data augmentation provided several important benefits for our study. One of the greatest benefits was the ability to determine the probability that the population was increasing in abundance. To our knowledge, the posterior probability of an increase in abundance could not be derived from frequentist analysis of these models. Another

important benefit was the ability to use informative priors based upon similar studies of gartersnakes. Informative priors were appropriate for this analysis because of the short duration of the study and the relatively sparse data caused by low capture probabilities. The use of informative priors did not affect posterior inference for most parameters but did shift the posterior distributions for annual survival to lower values. We prefer to base inference on the analysis using informative priors, because we think they accurately represent existing knowledge and thus provide more reliable posterior inference given the conditions of our study. In the case of endangered species more conservative estimates are appropriate for providing information upon which to base management goals and actions. Although low capture probabilities prevented our doing so here, the use of the data augmentation approach allows the estimation of the effects of individual covariates on capture and survival probabilities. We anticipate that use of Bayesian methods and additional study will provide quality information for the recovery of the San Francisco gartersnake throughout its range.

### Supplemental Material

Please note: The *Journal of Fish and Wildlife Management* is not responsible for the content or functionality of any supplemental material. Queries should be directed to the corresponding author for the article.

**Text S1.** Text file containing commented R code for running the  $p_t\gamma_t\Phi_t$  model with uninformative and informative priors in WinBUGS and calculating derived parameters from the Markov chain Monte Carlo output, including annual capture probabilities, per capita recruitment, and population growth rate.

Found at DOI: <http://dx.doi.org/10.3996/012011-JFWM-009.S1> (10 KB TXT).

**Table S1.** Microsoft Excel file containing data used in the analysis of San Francisco gartersnake (*Thamnophis sirtalis tetrataenia*) abundance, survival, recruitment, and population growth rate (CMR Data) and sex ratio and sexual size dimorphism (Sex Size Data).

Found at DOI: <http://dx.doi.org/10.3996/012011-JFWM-009.S2> (16 KB XLSX).

### Acknowledgments

We thank J. Powers for access to the study site, promotion of our study, and assistance with logistics. Housing was provided by J. Wade and R. Bennett of the Pescadero Conservation Alliance at their research station at Gazos Creek. We thank many biological technicians and volunteers, including J. Capps, S. Cloherty, K. Colgate, M. Feldner, B. Friermuth, E. Hellgren, D. Pearse, L. Pearse, M. Pilgrim, E. Taylor, Z. Thompson, J.D. Willson, and C. Winne, for assistance in the field and installation of traps and cover boards. P. Gore provided administrative support. G. Fellers, M. Herzog, three anonymous reviewers, and the Subject Editor provided valuable comments that improved an earlier version of this manuscript. J. Powers, N. Smith, M. Smith, C. Bettner, F.



Andrews, and Mike of Santa Cruz Hydroponics and Organics donated all cover board materials used in this project. Funding was provided by a grant from the U.S. Fish and Wildlife Service and a National Science Foundation Graduate Research Fellowship to M.A. Snakes were handled in accordance with the University of California–Davis Animal Care and Use Protocol 9699 and as stipulated in U.S. Fish and Wildlife Service Recovery Permits TE-170403 (2007 and 2008), TE-020548-5, and California Fish and Game Memorandum of Understanding (SC-009313, SC-009315).

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