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POPULATION AND DISTRIBUTION OF SWAINSON'S HAWKS (*BUTEO SWAINSONI*) IN CALIFORNIA'S GREAT VALLEY: A FRAMEWORK FOR LONG-TERM MONITORING

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Abstract.—The California Fish and Game Commission listed the Swainson's Hawk (*Buteo swainsoni*) as a state threatened species in 1983 in response to population reductions and habitat loss across the state. Human population increases, urbanization, and shifts in agricultural land use have the potential to affect California's Swainson's Hawk population. In 2005 and 2006, we conducted surveys to estimate the abundance and density of Swainson's Hawk breeding pairs in California's Great (Central) Valley, using a random sampling design stratified across dense, medium, and sparse nesting density strata. The sampling units comprised 2.59-km^2 (1-mile^2) US Public Land Survey System Sections, and the 2-yr survey covered an aggregate total of 682 sampling units (268 in 2005, 414 in 2006). Separate surveyors conducted independent surveys of 29 sampling units in 2006; based on these data, the estimated probability of detecting a single pair (if present) following the multiple-visits protocol was 0.81 (95% CI: 0.58–0.93). After applying this detection-probability correction and using generalized linear modeling of habitat associations to extrapolate density estimates throughout the study area, we estimated that the Great Valley supported 3218 (95% CI: 2271–4165) breeding pairs of Swainson's Hawks in 2005–2006. Our modeling of habitat associations showed crop diversity, alfalfa, and native vegetation as positively associated with the density of Swainson's Hawk breeding pairs, and orchards/vineyards negatively associated. Counts of breeding pairs were also highest in the middle latitudes of the Great Valley, which spans approximately 660 km from north to south. The predictive density model results had some areas of disagreement with the density strata used as basis for the stratified sampling design. To monitor the population status of this species throughout California, we recommend that our 2-yr sampling approach be expanded throughout the state and repeated every 5–10 yr. We also suggest this approach be used to monitor other special status raptor species to track population trend and distributional changes over time.

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KEY WORDS: *Swainson's Hawk*; Buteo swainsoni; *abundance*; *density*; *detection*; *distribution*; *population estimate*; *population monitoring*; *probability*; *sampling*; *stratified random*; *survey*.

POBLACIÓN Y DISTRIBUCIÓN DE *BUTEO SWAINSONI* EN EL VALLE CENTRAL DE CALIFORNIA: UN MARCO DE TRABAJO EL MONITOREO A LARGO PLAZO

RESUMEN.—La Comisión de Caza y Pesca de California listó en 1983 a *Buteo swainsoni* como una especie amenazada a nivel estatal, en respuesta a las reducciones poblacionales y a la pérdida de hábitat a través de este estado. El aumento de la población humana, la urbanización y los cambios en el uso del suelo dedicado a la agricultura pueden potencialmente afectar las poblaciones de *B. swainsoni*. En 2005 y 2006, realizamos censos para estimar la abundancia y la densidad de parejas reproductivas de *B. swainsoni* en el Valle Central de California, usando un diseño de muestreo al azar estratificado según estratos de densidad alta, media y baja. Las unidades de muestreo incluyeron áreas de 2.59 km^2 (1 mi^2) correspondientes al Sistema de Secciones de Tierras Públicas de los Estados Unidos. El censo, de dos años, abarcó un total agregado de 682 unidades de muestreo (268 en 2005, 414 en 2006). Los censistas realizaron muestreos independientes en 29 unidades de muestreo en 2006; basados en estos datos, la probabilidad estimada de detectar una sola pareja (de estar presente) siguiendo el protocolo de visitas múltiples fue de 0.81 (95% IC: 0.58–0.93). Luego de aplicar esta corrección de probabilidad de detección y usando modelos lineales generalizados de asociaciones de hábitat para extrapolar las estimaciones de densidad a través del área de estudio, estimamos que el Valle Central albergó 3218 (95% IC: 2271–4165) parejas reproductivas de *B. swainsoni* en 2005–2006. Nuestros modelos de asociaciones de hábitat indicaron que la diversidad de cultivos, la alfalfa y la vegetación nativa están positivamente asociados con la densidad de parejas reproductivas de *B. swainsoni*, mientras que los huertos y viñedos estan negativamente asociados. Los conteos de parejas reproductivas también fueron máximos en las latitudes medias del Valle Central, que se extiende por aproximadamente 660 km de norte a sur. Los resultados de los modelos predictivos de densidad tuvieron algunas áreas de desacuerdo con la densidad de estratos usados como base para el diseño del muestreo estratificado. Para monitorear el estatus poblacional de esta especie a lo largo de California, recomendamos que nuestro muestreo de dos años sea extendido a través del estado y repetido cada 5–10 años. También sugerimos que se use este enfoque para monitorear otras especies de rapaces de estatus especial para seguir las tendencias poblacionales y los cambios de distribución a lo largo del tiempo.

[Traducción del equipo editorial]

Swainson's Hawks (*Buteo swainsoni*) breed in the western United States and Canada, and winter in isolated areas of California, Mexico, Central America, and South America as far south as Argentina (Bechard et al. 2010, Kochert et al. 2011). They arrive at their breeding sites in the Great Valley (otherwise known as the Central Valley) of California during March and April, and depart for their wintering grounds between mid-August and late September (Airola et al. 2019). In California, 95% of the population breeds in the Great Valley, with smaller breeding populations in the Great Basin deserts and valleys of northeastern California, the Owens Valley of eastern California, and Antelope Valley in the Mojave Desert of southern California (Bloom 1980, California Department of Fish and Wildlife [CDFW] 1988, Anderson et al. 2007).

Historically, Swainson's Hawks occupied open native grassland, prairies, and shrub habitat throughout California. As native habitats were removed for the expansion of agriculture, cultivated lands also became an important part of Swainson's Hawk habitat, particularly where crop patterns supported abundant small rodent and insect prey (Bloom 1980, Bechard 1982, Estep 1989, Babcock 1995). Today, agricultural landscapes dominate the Great Valley, with relatively few areas of natural upland habitat remaining, such as grassland, vernal pools, and woodland (CDFW 2005). Some remnant riparian and wetland areas remain within portions of the valley, associated with rivers, other waterways, and floodplains; and the southern portion of the valley (e.g., San Joaquin Valley) includes some natural alkali sink and saltbush shrublands. (CDFW 2005).

Due to the dominance of agriculture in the Great Valley, most Swainson's Hawks breed near and forage in a variety of irrigated crops, grassland, and pasture (Bloom 1980, Woodbridge 1985, Estep 1989, Babcock 1995, Smallwood 1995). Alfalfa and other low-growing hay crops typically are the most frequently used foraging habitats in agricultural landscapes (Swolgaard et al. 2008, Estep 2009, Anderson et al. 2011), whereas use of most annually cultivated crops is more variable and dependent on seasonal changes in vegetation structure that influences access to prey. Mature orchards and vineyards generally are not suitable foraging areas, because the tall, perennial vegetation structure inhibits access to prey throughout the breeding season (Bechard 1982, Estep 1989, Babcock 1995, Swolgaard et al. 2008).

In the first statewide survey for breeding Swainson's Hawks, conducted in 1979, Bloom (1980) estimated a statewide population of 375 breeding pairs, and through a review of historical records, noted a statewide decline exceeding 90%. In response, in 1983 the California Fish and Game Commission listed the Swainson's Hawk as a threatened species under the California Endangered Species Act. A second statewide survey followed in 1986 and 1987, which resulted in an estimate of 550 breeding pairs (CDFW 1988).

Although the primary causes of population decline in California remain uncertain (Bloom 1980), loss and modification of habitat from agricultural conversion of native habitats and urbanization have likely contributed to population declines and regional shifts in the nesting distribution (Schlorff and Bloom 1984, Warner and Hendrix 1984, Schoenherr 1990, California Department of Conservation 2015). Given the distinctiveness of the Great Valley's Swainson's Hawk population and the persistence of threats to their habitat, there is great value in understanding how breeding population numbers and distribution change over time. In anticipation of continued landscape changes, we recognized the need for more comprehensive and accurate information on the distribution, population numbers, and densities of Swainson's Hawks in this portion of the species' range.

To understand the current population in the state and ultimately facilitate conservation efforts to maintain a sustainable breeding population, we developed a survey to estimate the statewide Swainson's Hawk population. Our goal was to design a study that could be used to compare current and past statewide population estimates. We also wanted the design to be modern, repeatable, and statistically robust enough to provide a baseline population estimate for comparison to future surveys.

As the original goal was to obtain a statewide population estimate, the surveys in 2005 covered the entire known range of Swainson's Hawks in the state. In 2006, we constrained the survey area to the Great Valley (excluding Great Basin deserts and valleys of northeastern California, the Owens Valley, and Antelope Valley, and southern portions of the Great Valley) because of concerns related to cost and large sample sizes in areas where few or no hawks had been detected, or in small, isolated areas where other survey efforts provided ample data (e.g., Butte Valley; Briggs et al. 2011). Because of the inconsistency in spatial coverage between the two years and because most of California's Swainson's Hawk population resides in the Great Valley (Bloom 1980, CDFW 1988, Anderson et al. 2007), our assessment in this report focuses on estimating the population size (i.e., number of breeding pairs) and mapping breeding densities in the Great Valley.

Study Area and Methods

Study Area. The study area encompassed the known distribution of breeding Swainson's Hawks in the Great Valley, as determined from prior data and expert opinion, generally corresponding to the low-elevation areas along the eastern and western edges of the Great Valley, north to Red Bluff and south to the Tehachapi Range (Fig. 1). We developed the study area based on the results of historic and recent studies, all known nesting observations recorded in the CDFW database, and consultation with Swainson's Hawk experts from the CDFW and Technical Advisory Committee.

Study Design. We employed a stratified random design to select sampling units throughout the portion of the Great Valley (81% of the area of this ecoregion) designated as our study area. Based on nesting densities known at the time and expert knowledge of available habitat, we divided the study area into three strata representing areas of presumed dense, medium, and sparse nesting density (Fig. 2). Using survey data from the first year (i.e., 2005) and previously known density estimates, as understood at the time by experts, we approximated the strata as follows: dense = >4 breeding pairs per 100 km^2; medium = 0.5–4 breeding pairs per 100 km^2; and sparse = <0.5 breeding pairs per 100 km^2. Sparse density strata made up 56% of the study area, medium 23% and dense 21%. The stratification of the random sampling in this way was intended to reduce variances within relatively homogeneous

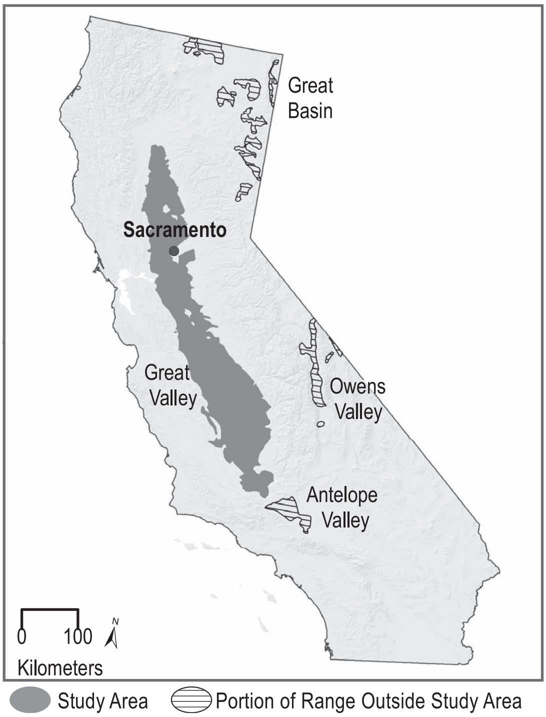

Figure 1. Depiction of the study area in California (Great Valley) and the areas within the known range but outside the study area. Taken as a whole, this was the known Swainson's Hawk breeding distribution in California at the initiation of this 2005 and 2006 survey effort.

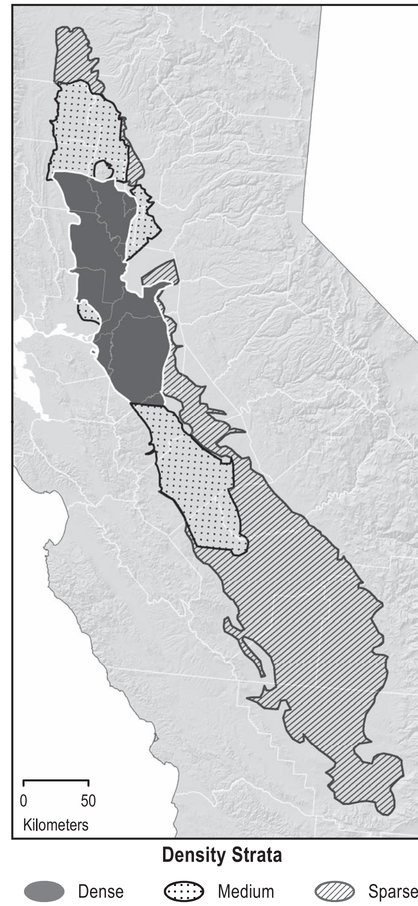

Figure 2. Strata representing dense, medium, and sparse Swainson's Hawk breeding-pair densities in California used as the basis for a stratified random survey design and in density modeling approach.

density strata and thereby produce more precise overall population estimates (Cochran 1977).

We used the US Public Land Survey Sections (PLSS) land-mapping system (USGS 2004) to create a set of survey quadrats within a sampling frame. The PLSS divides land into square townships consisting of 36 one-square-mile (2.59 km^2) sections, and road systems that had been built based on the PLSS often provided convenient access to sampling units. Using ArcGIS tools (v 9.0 ESRI, Redlands, CA, USA), we clipped the PLSS map layer to conform to the study area boundaries and compose the sampling frame. From within that sampling frame and each density strata, we then randomly selected PLSS sections to serve as sampling units. The effective area of the sampling units varied slightly due to factors such as distortions caused by curvature of the earth, land surveyor error, difficult terrain, and survey equipment error (USGS 2004). In addition, some sections on the edge of the study area were fragmented when the study area was overlaid. To reduce the PLSS sections that were irregular or fragmented, we only made available sections that were >1.3 km^2 (0.5 square-miles) for use in the sampling frame. The size of sections in the final sampling frame ranged from 1.35–3.37 km^2 (0.52–1.3 square-miles), with an average of 2.59 km^2 (1.0 square-miles). Private-property restrictions also precluded conducting complete surveys of some sampling units.

With the goal of increasing the precision of estimation, we allocated proportionately more sampling units to the dense stratum, where we expected the variance to be greatest, and proportionately the fewest sampling units to the sparse stratum, where we expected the variance to be lowest (Cochran 1977). We randomly selected different sets of

Table 1. Swainson's Hawk survey effort and summary results for 2005 and 2006, showing the number of units surveyed, units with detections, number of breeding pairs and average count of pairs per year and per density stratum. In 2005 we selected 268 sampling units with the majority of samples distributed in the dense and medium strata and fewer in the sparse strata. In 2006 we selected 414 sampling units all within the dense and medium strata.

		DENSITY STRATUM		
YEAR	SURVEY EFFORT AND SUMMARY RESULTS	SPARSE	MEDIUM	DENSE
2005	Units surveyed	40	58	170
	Units with detections	0	6	62
	Number of breeding pairs	0	7	89
	Average count of pairs where detected	NA	1.17	1.44
2006	Units surveyed	0	169	245
	Units with detections	NA	27	70
	Number of breeding pairs	NA	31	92
	Average count of pairs where detected	NA	1.15	1.31

sampling units for each survey year (see Table 1). To provide a basis for estimating the probability of our surveys detecting a breeding pair, we randomly selected 29 of the sampling units for duplicate surveys in 2006, and had two different individuals conduct independent surveys of those sampling units without knowledge of the other researcher's duplicative effort.

Survey Protocol. All surveys were conducted by experienced volunteers and CDFW staff following a standardized protocol developed for this study. We provided the surveyors with maps of their assigned sampling units, field forms, and survey instructions. Each surveyor attempted to find all breeding pairs within their assigned sampling units by visiting them multiple times to determine presence, minimize the potential for double counts, and maximize detection of pairs with nests. To count as a breeding pair, we required that surveyors observed both members of the pair in association with a nest or nesting area, or observed an adult or young in or near a nest. During each visit, the surveyors drove all accessible roads, walked portions of the unit, and sometimes used boats to enable scanning of all accessible and visible areas.

For each sampling unit, surveyors noted the number and timing of visits and the amount of time spent surveying per visit. Sampling units typically were visited 1–3 times during the breeding season. Some sampling units required multiple visits for adequate coverage; in this case, subsequent visits were spaced several days to >1 mo apart. Some sampling units only required one visit because they lacked suitable nest trees, or were already occupied by another species, e.g., a single nest tree in a unit occupied by nesting Red-tailed Hawks (*Buteo jamaicensis*). We encouraged observers to complete at least one survey per sampling unit when pre-nesting activity was greatest, paired birds were most obvious, and existing nests were more readily visible in deciduous trees that had not yet leafed out. In 2005, logistical delays resulted in late initial visits (late April) for some sampling units, with surveys continuing through mid-July. In 2006, all sampling units were surveyed between mid-March and mid-July.

Density Estimation. We used a model-based approach to estimate population size based on covariate associations from regression analysis, because this allowed us to assess how density varied spatially throughout the study area (Gregoire 1998). Specifically, we used generalized linear models (GLMs) to evaluate how the abundance of breeding pairs varied in relation to several environmental factors and to predict abundances at all PLSS sections in the study area.

We included several potential explanatory variables in the GLMs. We included latitude and its quadratic term because we expected abundance to be higher in the central latitudes of the Great Valley consistent with our delineation of sampling the strata and findings of other researchers (Gifford et al. 2012). We included alfalfa (percent cover for section), which others have found to be positively associated with breeding habitat suitability (Smallwood 1995, Swolgaard et al. 2008). We included native vegetation (percent cover in section) based on previous research showing the importance of grasslands and riparian vegetation (Smallwood 1995, Estep and Dinsdale 2012). We also included orchards and vineyards (percent cover for section), which may negatively impact habitat quality (Swolgaard et al. 2008). We included crop diversity (total number agricultural crop types grown in the section) as another potential predictor of habitat quality based on findings from elsewhere that found proximity to, and amount of, agriculture increases habitat quality (Briggs et al. 2011), and that different crops provide optimal foraging conditions in different seasons or in different growth stages (Babcock 1995, Estep and Dinsdale 2012). Lastly, we included presumed density strata as a categorical variable in our modeling and estimation approach. We used the county land-use data that was collected nearest in time to the date of our study; this differed by county and dates ranged from 1994 to 2009 (California Department of Water Resources 2016). In California, updates to these land-use data are made if there are significant land-use changes within a county, and thus we believe that the county-level data used for our analysis were appropriate to determine cover and crop diversity values in each PLSS section. We used a combination of Class 1 and Subclass 1 attributes from this data source to identify individual crops like alfalfa, and grouped other classifications together such as orchard and vineyard, and native vegetation (riparian areas, grasslands, etc.). We z-transformed all covariates by subtracting the mean and then dividing by the standard deviation.

We fit GLMs with a log-link assuming a Poisson distribution for the response variable (observed count of breeding pairs per section). We confirmed that this probability distribution was appropriate for our data (i.e., mean count per section = 0.32, variance of counts = 0.43). We used an information-theoretic approach to model selection and inference using Akaike's Information Criterion (AIC, Burnham and Anderson 2002). We fit 48 models containing all noncollinear combinations of the covariates listed above plus an intercept-only model. We did not include latitude and density stratum together in any of these models because they were moderately correlated ($r < -0.30$). We considered potential interactions between agriculture and native habitats (Bridle et al. 2009, Heath et al. 2017). Specifically, we considered interactions between native vegetation and each of our three measures of agriculture: alfalfa, orchards, and crop diversity. Therefore, we fit an additional set of 12 models including all combinations of each interaction with the other model covariates. This summed to a total of 84 models. We applied model-averaging of all models in the top 95% of model weights to estimate "apparent" abundance ($N_{apparent}$) for every section in the sampling frame before adjusting for detection probability. We did this by multiplying the abundance estimate from each model for each section by the model weight and then summing those weighted products for each section (Cade 2015).

As noted earlier, we conducted duplicate surveys at 29 sites to allow us to estimate detection probability of our survey method. We fit an N-mixture model without covariates to estimate the average probability of a single pair being detected (if present) by an observer at sites where there were two independent surveys (Royle 2004). We then applied a correction factor based on the detection probability (p) estimated from the N-mixture model to estimate the true abundances (N_{true}) of breeding pairs for each section in the sampling frame ($N_{true} = N_{apparent} / p$). We summed these abundances to get an estimate of total population size for the Great Valley. We used parametric bootstrapping (10,000 resamples) to incorporate uncertainties for both $N_{apparent}$ and p in generating an interval estimate (e.g., 95% confidence interval) for population size in the study area (Efron 1982). Lastly, we converted the abundance estimates for sections to density by dividing by the section areas. We then mapped how density varied across the Great Valley.

To validate our model with a secondary estimate of population size, we used classical design-based inference to alternatively estimate population size. Specifically, we used stratified random sampling equations to estimate population size, and its uncertainty, in each stratum and for the entire study area (Cochran 1977). We used the delta method to correct the interval estimate of apparent abundance using our estimate of detection probability from N-mixture modeling (Link and Nichols 1994).

We took a number of additional steps to assess the fit of each of the top models. First, we performed a deviance goodness of fit test, for which we interpreted confirmation of the null hypothesis (e.g., $P > 0.05$) to indicate that our use of Poisson regression was sound (Kutner et al. 2005). Second, we computed adjusted pseudo R^2, which we interpreted as the proportion of variance explained by a top model in comparison to the intercept-only model (McFadden 1974). Third, we compared similarity of extrapolated abundance estimates from each of the top models.

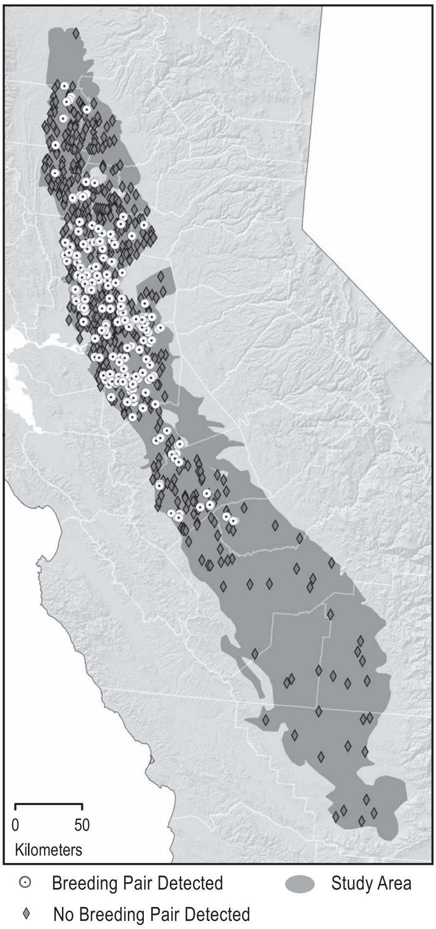

Figure 3. Distribution of sampling units and Swainson's Hawk survey results for both 2005 and 2006. In total, 219 breeding pairs were detected from the sampling units surveyed.

Results

In 2005, the surveyors detected 96 breeding pairs of Swainson's Hawks in 68 of the 268 sampling units selected, and in 2006, the surveyors detected 123 pairs in 97 of the 414 sampling units selected (Table 1, Fig. 3). The 2005 survey yielded no detections in the sparse density stratum (Table 1).

The abundance modeling showed that crop diversity, alfalfa, and native vegetation were positively associated with Swainson's Hawk pair counts, whereas orchards/vineyards were negatively associated (Table 2). Counts were also highest in the middle latitudes of the Great Valley, but were not strongly associated with the density strata variable, which appeared to reflect the small sample size in the sparse stratum (Table 1). We also found strong evidence of a positive interaction between native vegetation and crop diversity. We found moderate evidence of a positive interaction between native vegetation and alfalfa and a negative interaction between native vegetation and orchards/vineyards.

From the N-mixture modeling we estimated a detection probability, for a surveyor during the multiple-visits protocol, of 0.81 (95% CI: 0.58–0.93). After applying the detection probability correction and using the final GLM model to extrapolate abundances throughout the study area, we estimated a total of 3218 (95% CI: 2271–4165) breeding pairs in the study area (Table 3). This estimate included 690 pairs (95% CI: 337–1043) within the sparse-density stratum that constituted 56% of our study area.

Our alternatively calculated design-based estimate closely validated the modeling estimate for the moderate and dense strata (e.g., 2489 vs. 2528, respectively; Table 3). We acknowledge that the modeling provided a higher estimate for the low-density stratum than from the design itself (e.g., 690 vs. 0). We provide both estimates, but we also reiterate that we believe sampling in the low-density strata was too low to provide a solid basis for design-based inference. Conversely, we confirmed that our modeling did an acceptable job of extrapolating abundance for the purpose of estimating population size. Our deviance tests demonstrated that our use of Poisson regression was appropriate ($P > 0.9$ for all top models). Adjusted pseudo R^2 ranged from 0.11 to 0.12 for those models suggesting that our mapping of spatial variation in density should be limited to coarse-scale inferences consistent with our focus on total population size. This conclusion was supported by our finding that there was little variation in average extrapolated abundance among the top models (Table 2).

The predicted density map had some disagreement with the density strata used to design the study (Fig. 4). The model predicted areas of higher-than-expected density in a large portion of the sparse- and medium-density strata in the southern counties of the Great Valley, as well as in the sparse-density strata bordering the study area east of the cities of Sacramento, Stockton, and Modesto. Unfortunately, none of the sampling units surveyed in the sparse stratum during 2005 were in these areas of predicted higher density and these areas were not surveyed in 2006. The model also produced divergent results in the northern portion of the study area, from Yolo,

Table 2. Model selection for estimating spatial variation in Swainson's Hawk counts throughout the Great Valley of California, USA, during 2005 and 2006. We show the top five models with covariates summing to 95% of total model weights and an intercept-only model. Local abundance represents the study area average model prediction of hawk pairs per each approximately 2.59-km^2 survey section.

	Model Selection		Effect Size[b, c]								
Model[a]	Delta AIC	Model Weight	Intercept	Crop	Alfalfa	Orchard	Native	Interaction	Latitude	Latitude2	Local Abundance
Alfa + Orch + Crop*Nati + Lat + Lat2	0.00	0.51	**−1.44**	**0.56**	**0.16**	**−0.33**	0.13	**0.22**	**1.54**	**−1.53**	16
Alfa*Nati + Orch + Crop + Lat + Lat2	2.03	0.18	**−1.40**	**0.53**	**0.32**	**−0.35**	**0.24**	**0.37**	**1.45**	**−1.47**	17
Alfa + Orch + Crop + Lat + Lat2	3.89	0.07	**−1.51**	**0.53**	**0.13**	**−0.38**	NA	NA	**1.54**	**−1.50**	16
Orch + Crop*Nati + Lat + Lat2	4.20	0.06	**−1.38**	**0.56**	NA	**−0.40**	0.05	**0.21**	**1.45**	**−1.52**	17
Alfa + Orch + Crop + Nati + Lat + Lat2	4.42	0.06	**−1.51**	**0.55**	**0.16**	**−0.36**	**0.13**	NA	**1.54**	**−1.51**	17
Alfa + Orch*Nati + Crop + Lat + Lat2	5.12	0.04	**−1.39**	**0.54**	**0.15**	−0.21	0.34	**0.36**	**1.54**	**−1.53**	17
Alfa + Crop*Nati + Lat + Lat2	5.73	0.03	**−1.36**	**0.52**	**0.21**	NA	0.19	**0.24**	**1.67**	**−1.59**	17
Intercept only	145.41	0.00	**−1.14**								32

[a] Model terms: Crop = crop diversity, Orchard (Orch) = orchard/vineyard, Native (Nati) =native vegetation, Alfa = Alfalfa, Lat = Latitude, Lat2 = Quadratic of Latitude

[b] Bold font indicates 95% confidence interval did not overlap zero

[c] Average predicted abundance extrapolated across the study area (pairs/100 km^2). Not corrected for detection probability.

[d] Three interactions (*, crop, alfalfa, orchard/vineyard) with native vegetation were considered. See model terms to see which one applies in each case.

Sutter, and Placer Counties northward. Here, the predictive density model showed a mix of medium and dense areas, whereas the density strata defined those areas as uniformly dense or medium. Similarly, the density model showed Tehama County as a mix of medium and sparse density, whereas the density strata defined these areas as sparse density. The area of agreement between the density model and strata is in the most southern portion of the Great Valley, inclusive of Kern County and in southern Tuolumne and King Counties, and within a majority of the area designated as the dense strata.

DISCUSSION

When designing our study, the intent was to design framework that could be applied to other special-status species as a means of assessing population health at similar spatial scales, with the recognition that application may vary somewhat based on species habitat, biology, and behavior. We focused on Swainson's Hawks because we recognized that populations in California's Great Valley are unusual in that they may represent a somewhat distinct portion of the larger North American Swainson's Hawk population (England et al. 1995, Hull et al. 2008, Airola et al. 2019) and because understanding population trends over time is of great conservation importance.

The Swainson's Hawks of the Great Valley are distinctive in their range, migratory patterns, and genetics (England et al. 1995, Hull et al. 2008, Airola

Table 3. Population estimates of Swainson's Hawks in the Great Valley of California, USA, during 2005 and 2006. The model-based estimate, which considers how abundance varied spatially with various environmental factors known to affect habitat quality, represents our best estimate for the total population. The design-based estimate is included as comparison to validate our modeling within the medium and dense strata, however, limited sampling within the sparse strata precluded accurate design-based inferences in these areas.

Population Estimate Type and Parameters	Population Estimates		
		Density Strata	
	Total	Medium and Dense	Sparse
Model estimate			
Number of breeding pairs	3218	2528	690
95% CI	2271–4165	1848–3208	337–1043
Coefficient of Variation	0.15	0.14	0.26
Design estimate			
Number of breeding pairs		2498	
95% CI		2241–2755	
Coefficient of Variation		0.05	

et al. 2019). Banding and telemetry studies have demonstrated that the Great Valley hawks winter from west-central Mexico to central South America, unlike the hawks from other areas of the range that winter primarily in Argentina (Bradbury 2001, Wheeler 2003, Airola et al. 2019). The differentiation among microsatellite genotypes of Swainson's Hawk populations in the Great Valley of California, and populations in Great Basin, Great Plains, and southwestern deserts of North America suggest some level of gene separation among the populations (Hull et al. 2008).

We found a positive relationship between the amounts of native vegetation and crop diversity, a positive relationship between native vegetation and alfalfa, and a negative relationship between native vegetation and orchards/vineyards. These results suggest a synergistic effect of these factors on Swainson's Hawk abundance, especially native vegetation and crop diversity. Previous research suggests the native vegetation of trees, especially in riparian habitats, may increase nesting opportunities (Estep and Dinsdale 2012) and that crop diversity may widen seasonal availability of suitable foraging areas (Babcock 1995, Estep and Dinsdale 2012). We speculate that the combination of both factors further augments habitat quality by increasing total vegetative diversity available for foraging through the provision of native grasslands (Smallwood 1995) and closer configuration of nesting habitat and foraging areas on agricultural lands (Briggs et al. 2011). Our results also agree with previous research that showed a positive correlation between Swainson's Hawk presence and alfalfa (Swolgaard et al. 2008, Estep 2009, Anderson et al. 2011) and negative correlation with orchards and vineyards (Bechard 1982, Estep 1989, Babcock 1995, Swolgaard et al. 2008).

Our estimate of 3218 Swainson's Hawk breeding pairs in the Great Valley is substantially larger than the earlier statewide estimates (Bloom 1980 and CDFW 1988). The 1979 survey resulted in an estimate of 375 breeding pairs across the state, with 280 pairs in the Great Valley, and Bloom (1980) speculated that as many as 17,136 pairs could have occurred in California historically. That study design was not repeatable, however, and was insufficient to generate robust estimates of the statewide population size and density distribution. The second statewide survey, conducted in 1986 and 1987, produced a statewide estimate of 550 breeding pairs, with 430 pairs in the Great Valley (CDFW 1988). This study design was a repeatable approach based on extrapolating known densities in four areas of the Great Valley across the rest of California using general habitat patterns, but still was not considered sufficiently robust to accurately estimate the statewide or Great Valley populations. Although these estimates are not strictly comparable because of different survey coverage and analytical methodologies, we speculate that populations of Swainson's Hawk in California may be on the rise given the results of this study and data obtained thru 2018 (CDFW unpubl. data). The differences of estimates between earlier surveys and this study may be indicative of a true population increase in the Great Valley during the preceding 25 yr span. However, available habitat has likely declined during this period due to urbanization and changing crop patterns, primarily expansion of unsuitable orchards and vineyards (California Department of Conservation 2015). Therefore, the causes for the possible increase of the breeding population remain unclear. The higher estimate from our study may also at least partly reflect the more robust sampling and analyt-

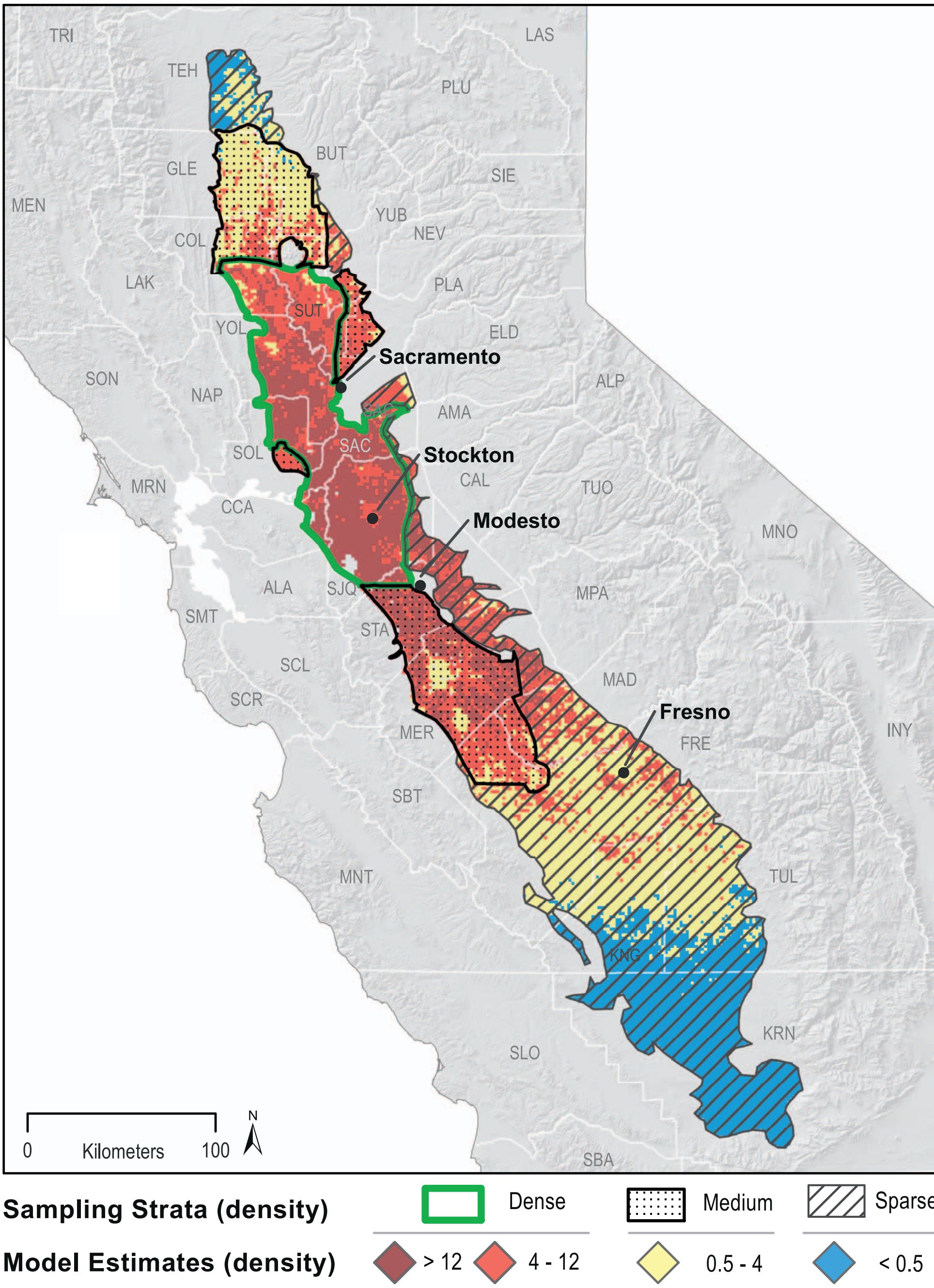

Figure 4. Estimated densities of Swainson's Hawk breeding pairs in the Great Valley of California, USA, during 2005–2006. These estimates, based on modeling of survey data, are compared against strata used in the sampling design (breeding pairs per 100 km^2: dense = >4; medium = 0.5–4; and sparse = <0.5). Results suggest that we underestimated true density when we assigned density ranges to these strata.

ical methods implemented in our study relative to earlier studies.

Looking at our study design retrospectively, we recognize there are areas where improvements could be made. As mentioned above, the predictive density model had some areas of disagreement with the density strata we used to design the surveys. In the case of the southern portion of the Great Valley, some areas had not been sufficiently surveyed at the time of the study, thus the assumed strata density actually underestimated the density. For example, more recent surveys have indicated some areas within the sparse stratum have proven to support larger-than-expected populations (Estep and Dinsdale 2012). In the case of the area east of Sacramento, Stockton, and Modesto, which has not been surveyed sufficiently to date, it may be that this area is well suited to Swainson's Hawks because of high crop diversity (total number of agricultural crop types in the section) and/or abundant alfalfa and native vegetation. Another possibility for these disagreements, however, is that our model overestimates density in some areas because it does not adequately represent the availability of suitable nest trees. A similar case may pertain to the areas of disagreement in the northern portion of the Great Valley starting in the northeastern portion of Colusa County and northern portion of Sutter County. Lastly, another reason for the difference between the density strata and the modeled density estimates may be that the strata were not corrected for detection probability and were based on apparent density rather than true density.

Based on the results of this study, we offer the following recommendations as potential ways to improve the study design for Swainson's Hawks in California or for other species for which this large-scale design might be suited, and thus improve the precision of estimates of numbers of breeding pairs. First, whenever possible, we recommend defining density strata to form the basis for the stratified random design based on comprehensive information from previous surveys and modeling results rather than expert opinion. This will help ensure that future efforts to assess statewide populations are reproducible and comparable across years. Second, to better capture population density across the study area, we recommend that surveys be distributed across the entire range of the study species within the study area, including areas thought to have lower breeding densities of the target species or none at all. Third, the design should include repeat surveys at a high proportion of sites sufficient to estimate temporal and spatial variation in detection probabilities within a hierarchical modeling structure (Kery and Royle 2016). Fourth, to arrive at the optimal number of samples to increase estimate precision and decrease variance, a power analysis or some other similar analysis should be conducted.

For Swainson's Hawks specifically, we recommend including areas of disagreement among our modeling approaches in future survey efforts to determine hawk presence there, and refining the predictive model based on those results. We also recommend using a nest-tree layer, including lone oak trees, oak groves, and mature roadside trees in the density model for Swainson's Hawks in California. Our model likely would have benefited from such tree data but no such habitat layer was available at the time of study. We recognize the importance of regular surveys for determining changes in distribution, density, and population health over time. For this reason, we suggest replicating our stratified random survey method every 5 or 10 yr, to arrive at a model-based population estimate (Pollock et al. 2002). This would support monitoring long-term population trends and interactions with broad-scale patterns of agricultural land use and urbanization. Integrated modeling methods also could be applied to combine data from the intensive periodic surveys with annual population information derived from other sources such as citizen science (Pacifici et al. 2017).

Finally, given the model results and the correlation between parameters, we believe that the combination of native habitats and agricultural heterogeneity, other than orchards and vineyards, is likely to enhance biodiversity in a highly modified environment such as California's Great Valley (Benton et al. 2003, Green et al. 2005). We suggest that the application of reconciliation ecology, one that balances diverse agricultural management with conservation of some native habitats (e.g., riparian areas and grasslands), may be an effective approach to maintaining productive habitats for Swainson's Hawk and many other wildlife species in California that have similar associations with native and agricultural land habitats (Rosenzweig 2003).

In this study we demonstrate an assessment is feasible for estimating the population size and density of breeding pairs at a statewide-level in California. In particular, we validated the population estimate using both model- and design-based approaches in medium- and high-density areas where sampling coverage was reasonable, and we expect that a similar assurance of accuracy could be achieved in low-density areas given greater sampling effort. The understanding of how a species is distributed across its range, how the population changes over time, and what habitat, land use, or other factors influence these changes, represents high-value information for conservation and recovery planning efforts. For Swainson's Hawks, these results provide baseline data to compare estimates and distribution over time, and this study design can be applied again in California or be broadened to other areas of the Swainson's Hawk's North American range. More broadly, this study design, along with recommendations for improvement, can be used as a model for monitoring other special-status raptor species to assess population health over time across a large area.

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