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Authors
Dybala, Kristen E.
Sesser, Kristin A.
Reiter, Matthew E.
et al.

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RESEARCH

Priority Bird Conservation Areas in California's Sacramento–San Joaquin Delta

Kristen E. Dybala[1], Kristin A. Sesser[1,2], Matthew E. Reiter[1], W. David Shuford[1,3], Gregory H. Golet[4], Catherine Hickey[1], Thomas Gardali[1,5]

ABSTRACT

Conserving bird populations is a key goal for management of the Sacramento–San Joaquin Delta ecosystem and is likely to have effects well beyond its boundaries. To inform bird-conservation strategies, we identified Priority Bird Conservation Areas for riparian landbirds and waterbirds in the Delta, defined as the most valuable 5% of the landscape for each group. We synthesized data from 2,547 surveys for riparian landbirds and 7,820 surveys for waterbirds to develop predictive distribution models, which then informed spatial prioritization analyses. We identified a total of 26,019 ha that are a high priority for conserving riparian landbirds, waterbirds, or both, representing the most important places in the Delta to protect and manage, as well as strategic areas where adjacent restoration could expand valuable habitat. These Priority Bird Conservation Areas include the Yolo Bypass Wildlife Area, Cosumnes River Preserve, Stone Lakes National Wildlife Refuge, and bufferlands that surround the Sacramento County Regional Sanitation District. However, we also found that over 60% of the Priority Bird Conservation Areas are not currently protected, indicating a vulnerability to changes in land cover or land use. We recommend advancing strategies for bird conservation in the Delta by developing more specific objectives and priorities, extending these analyses to include other bird species, and planning to mitigate the loss of Priority Bird Conservation Areas where they are most vulnerable to land cover change. The predictive models and analysis framework we developed represent the current state of the science on areas important to bird conservation, while also providing a foundation for an evolving bird-conservation strategy that reflects the Delta's continuously evolving knowledge base and landscape.

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* Corresponding author: *kdybala@pointblue.org*
1 Point Blue Conservation Science
Petaluma, CA 94954 USA
2 Current address: California Rice Commission
Sacramento, CA 95814 USA
3 Retired
4 The Nature Conservancy
Sacramento, CA 95811 USA
5 Current address: Audubon Canyon Ranch
Stinson Beach, CA 94970 USA

KEY WORDS

California, Central Valley, conservation planning, landbird, riparian, shorebird, waterfowl, species distribution model, zonation

INTRODUCTION

California's Sacramento–San Joaquin Delta provides key habitat for an abundant and diverse bird community (Dybala et al. 2020). Despite extensive modifications from the historical Delta landscape (Whipple et al. 2012; DSC 2022), more than 50,000 ha of wetlands, grasslands, shrublands, and forest continue to support the bird community (Schwenkler 2019). In addition, some agricultural lands—such as rice, corn, alfalfa, grains, and irrigated pasture—provide habitat for some bird species (Swolgaard et al. 2008; Pandolfino and Smith 2011; Shuford et al. 2019; Peterson et al. 2020). This diverse mosaic of land-cover classes, at the confluence of several rivers, contributes to the Delta's important role in supporting bird populations in California (Dybala et al. 2020), with the Delta region repeatedly highlighted as a priority now and under future climate change (Stralberg et al. 2011; Veloz et al. 2017; Point Blue Conservation Science c2020). Thus, effective planning and implementation of strategies for bird conservation in the Delta are likely to be valuable well beyond the boundaries of the Delta by contributing to meeting broader regional conservation goals for the San Francisco Estuary and Central Valley (Sloop et al. 2018; CVJV 2020; SFEP 2022), statewide conservation goals laid out in California's 30x30 Initiative (CNRA 2022), and habitat for the millions of birds that migrate along the Pacific Flyway each year (Rosenberg et al. 2016; Senner et al. 2016; NAWMP 2019).

Within the Delta's boundaries, providing bird habitat and migratory corridors are listed among the sub-goals for protecting, restoring, and enhancing the Delta ecosystem (Water Code § 85302(e) and § 85054; DSC 2013). Core strategies for achieving these and other ecosystem goals include prioritizing the protection and restoration of land where possible to restore ecosystem function, reestablishing land–water connections, and restoring native vegetation and habitat for native species over large scales (DSC 2022). Specific targets have been recently adopted for the net increase in native vegetation communities by 2050, and six Priority Habitat Restoration Areas have been identified as offering the most promising opportunities for restoring ecosystem function at appropriate elevations (DSC 2022). To ensure these conservation and restoration priorities will benefit birds, they could be further refined by better characterizing the current distributions of bird species in the Delta and the specific areas of the Delta landscape that provide suitable habitat for many species. Prioritizing the protection, enhancement, and effective management of these areas—as well as the restoration of adjacent areas to enlarge them and improve connectivity between them—is likely to provide the most benefit to the Delta bird community.

Here, we used existing bird survey data collected in the Delta and surrounding areas of the Central Valley to identify Priority Bird Conservation Areas and inform conservation, management, and restoration plans in the Delta. Specifically, we developed distribution models for nine riparian landbird species and six groups of waterbird species, which we then used to inform spatial prioritization analyses and identify areas within the Delta that currently provide habitat suitable for the largest number of riparian landbird species, waterbird groups, or both. We also evaluated the extent to which these areas may be vulnerable to changes in land cover and land use, and how these analyses can be used to refine priorities and strategies for bird conservation as the Delta landscape evolves.

MATERIALS AND METHODS

Data Collection

We compiled survey data for riparian landbirds and waterbirds collected by Point Blue Conservation Science and partners throughout and beyond the Delta for use in developing the distribution models.

Riparian Landbird Surveys

All riparian landbird surveys consisted of point counts, a standardized bird survey method in which a trained observer records all individual birds detected within a short period of time, along with their estimated distance from the survey location (Ralph et al. 1995). The majority

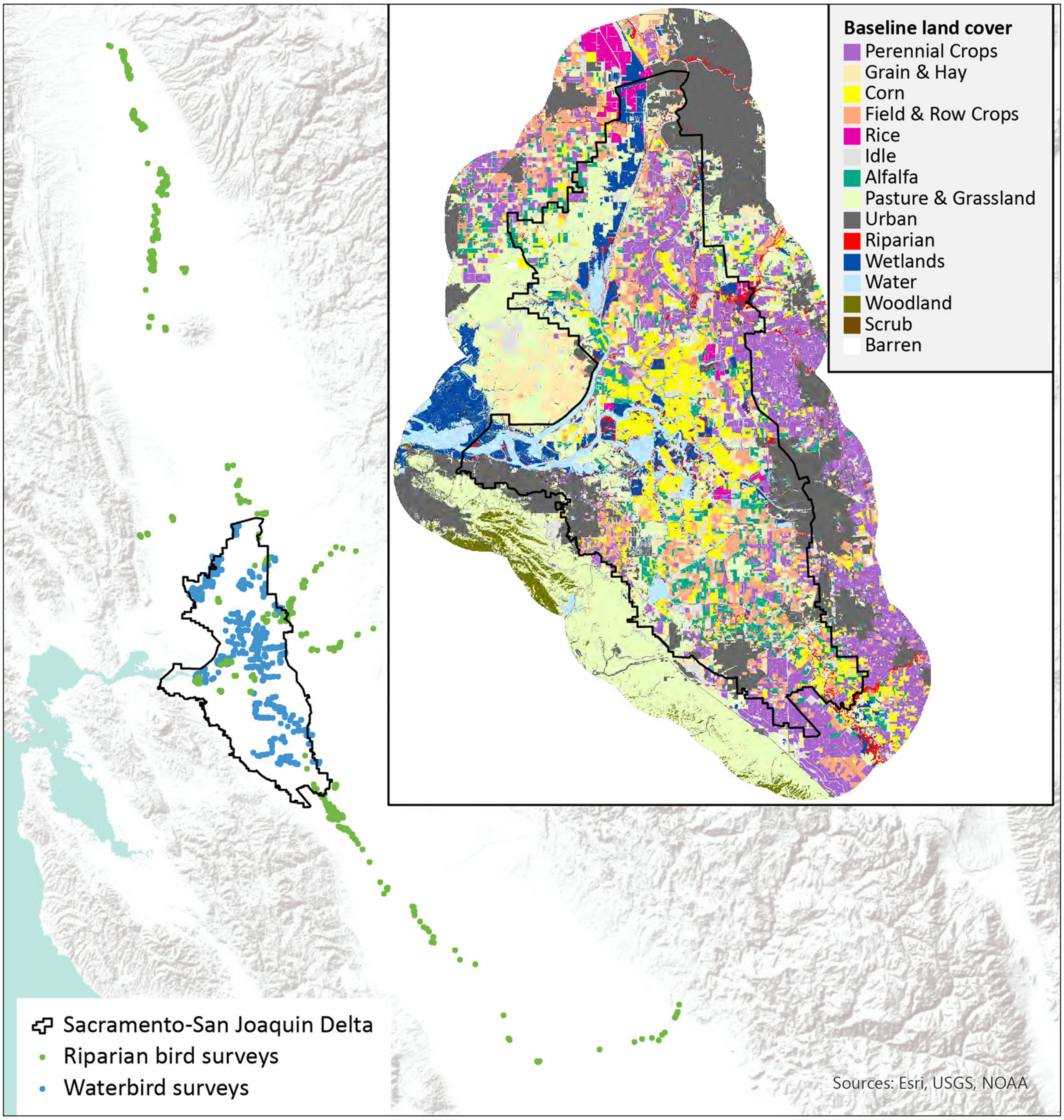

Figure 1 Location of riparian landbird and waterbird surveys, shown with the legal boundary of the Sacramento–San Joaquin Delta, and (*inset*) major land-cover classifications within the Delta and surrounding 10 km for the 2018 baseline conditions.

of these data were collected as part of a broad-scale monitoring effort in the Central Valley to establish baseline information on the population density and distribution of riparian birds (Gilbert et al. 2013; Figure 1); these surveys were intended to represent the range of available riparian vegetation conditions—including on both private and public lands—and were thus conducted within randomly-selected 100-m x 100-m grid cells located within 2 km of the main stems of major rivers that had at least a 60% riparian vegetation cover (GIC 2012). These surveys were conducted in 2012 and 2013 along the Sacramento and San Joaquin rivers, and in 2017 along the lower Sacramento, lower San Joaquin, Cosumnes, and Mokelumne rivers. We supplemented these data with additional surveys conducted by Point Blue Conservation Science and the California Department of Water Resources (2011–2019), which included a combination of long-term monitoring sites and riparian restoration sites on both private and public lands. We excluded survey locations from the supplemental survey data when they were less than 90 m from one of the randomly-selected survey locations; and where supplemental survey locations were less than 90 m from each other, we randomly selected one to remove. We also excluded locations where only a single survey had been conducted; and where more than four surveys had been conducted, we included only the four most recent surveys. To develop robust distribution models, we included all remaining surveys throughout this broad geographic extent to maximize the number of detections of each species across a range of riparian vegetation conditions. The final data set included a total of 2,547 riparian landbird surveys from 716 unique locations throughout the Central Valley, approximately 30% of which were within or immediately adjacent to the Delta.

All surveys were conducted using a similar protocol consisting of 5-minute surveys at each point count survey location, conducted during the peak of the breeding season in May and June. Our analysis focused on 9 of the 12 riparian focal species selected by the Central Valley Joint Venture as representative of a broad range of life histories and associations with riparian vegetation subclasses (Table 1; Dybala et al. 2017). The remaining three focal species—Least Bell's Vireo (*Vireo bellii pusillus*), Western Yellow-billed Cuckoo (*Coccyzus americanus occidentalis*), and Bank Swallow (*Riparia riparia*)—were all absent or extremely rare in the data set. These three species are all included on federal and/or state threatened and endangered species lists (Dybala et al. 2017) and have very limited distributions that are more effectively surveyed using specialized field methods (Howell et al. 2010; BAN–STAC 2013; Halterman et al. 2016); we excluded them from this analysis.

Because detection probability diminishes with distance from the survey location (Buckland et al. 2001), we limited our analysis to detections within 50 m of the survey location. Thus, we considered a species to be present (1) at a survey location if it was ever detected within 50 m during any of the included surveys at that location, including detections not in riparian vegetation, and absent (0) if it was not detected. We assumed that detecting a species within 50 m at least once over at least two surveys was a useful index of occupancy at that location, but we recognize that some apparent absences may include species that were present but not detected within 50 m (Seavy et al. 2009). As an index of the relative abundance of each species at each location, we used the maximum number of individuals detected within 50 m during any one of the included surveys. As an index of survey effort at each location, we calculated the total area within a 50-m radius multiplied by the total number of surveys conducted.

Waterbird Surveys

All waterbird surveys that we included in this analysis were conducted during the fall (July 15–November 15) and winter (November 17–March 5) seasons, 2013–2014, and 2014–2015, as part of a study to examine the relative value of wetlands and agricultural crops to waterbirds in the Delta (Shuford et al. 2019). Survey locations consisted of stratified random samples intended to cover a range of suitable land-cover classes, including alfalfa, corn, irrigated pasture, managed wetlands, rice, and winter wheat (Figure 1). Winter wheat was only available during the winter season, and we considered corn to be available as suitable habitat only after the fall harvest, which occurred relatively late in our fall season. Thus, although a few surveys in corn were conducted in late fall, we excluded corn from consideration in the analysis of fall data, to avoid overestimating its use throughout the fall season.

Similar to a point count survey, waterbird surveys consisted of counting all individuals detected

Table 1 Study species included in the distribution modeling and prioritization analyses. (**A**) Riparian landbird species. (**B**) Waterbirds groups. Species with special conservation status include species listed as Threatened under the California Endangered Species Act (CDFW 2021) and California Bird Species of Special Concern (Shuford and Gardali 2008), as indicated by footnotes. Also shown are the prevalence of each species or group in the survey data (proportion of survey locations at which they were detected) and maximum abundance index for a single survey location. For riparian landbirds, the prevalence and abundance index data are provided for the full data set and just for survey locations within the Delta. For waterbirds, the prevalence and abundance index data are shown by season.

		Prevalence		**Maximum abundance index**	
A.	**Riparian landbird species**	**Total**	**Delta**	**Total**	**Delta**
	Nuttall's Woodpecker (*Picoides nuttallii*)	0.42	0.27	3	3
	Ash-throated Flycatcher (*Myiarchus cinerascens*)	0.61	0.35	4	4
	Black-headed Grosbeak (*Pheucticus melanocephalus*)	0.52	0.31	4	3
	Lazuli Bunting (*Passerina amoena*)	0.13	0.04	3	2
	Common Yellowthroat (*Geothlypis trichas*)	0.23	0.41	3	3
	Yellow Warbler (*Setophaga petechia*) [a]	0.09	0.08	3	3
	Spotted Towhee (*Pipilo maculatus*)	0.83	0.67	8	4
	Song Sparrow (*Melospiza melodia*) [b]	0.44	0.81	7	5
	Yellow-breasted Chat (*Icteria virens*) [a]	0.04	0.01	2	1
B.	**Waterbird groups**	**Fall**	**Winter**	**Fall**	**Winter**
	Geese	0.14	0.30	8,174	4,543
	Greater White-fronted Goose (*Anser albifrons*) [b]				
	Snow Goose (*Anser caerulescens*)				
	Ross's Goose (*Anser rossii*)				
	Cackling Goose (*Branta hutchinsii*)				
	Canada Goose (*Branta canadensis*)				
	Dabbling ducks	0.18	0.27	4,004	7,279
	Wood Duck (*Aix sponsa*)				
	Gadwall (*Mareca strepera*)				
	American Wigeon (*Mareca americana*)				
	Mallard (*Anas platyrhynchos*)				
	Blue-winged Teal (*Spatula discors*)				
	Cinnamon Teal (*Anas cyanoptera*)				
	Northern Shoveler (*Spatula clypeata*)				
	Northern Pintail (*Anas acuta*)				
	Green-winged Teal (*Anas carolinensis*)				
	Diving ducks	0.03	0.16	127	4,442
	Canvasback (*Aythya valisineria*)				
	Ring-necked Duck (*Aythya collaris*)				
	Lesser Scaup (*Aythya affinis*)				
	Bufflehead (*Bucephala albeola*)				
	Common Goldeneye (*Bucephala clangula*)				
	Hooded Merganser (*Lophodytes cucullatus*)				
	Common Merganser (*Mergus merganser*)				
	Ruddy Duck (*Oxyura jamaicensis*)				
	Cranes	0.17	0.22	472	607
	Greater Sandhill Crane (*Antigone canadensis tabida*) [c]				
	Lesser Sandhill Crane (*A. c. canadensis*) [a]				

Table 1 *continued*

B.	**Waterbird groups** *(continued)*	**Fall**	**Winter**	**Fall**	**Winter**
	Shorebirds	0.19	0.20	4,748	2,753
	Western Sandpiper (*Calidris mauri*)				
	Least Sandpiper (*Calidris minutilla*)				
	Dunlin (*Calidris alpina*)				
	Black-necked Stilt (*Himantopus mexicanus*)				
	American Avocet (*Recurvirostra americana*)				
	Greater Yellowlegs (*Tringa melanoleuca*)				
	Lesser Yellowlegs (*Tringa flavipes*)				
	Long-billed Dowitcher (*Limnodromus scolopaceus*)				
	Short-billed Dowitcher (*Limnodromus griseus*)				
	Wilson's Snipe (*Gallinago delicata*)				
	Herons/Egrets	0.55	0.32	105	46
	Great Blue Heron (*Ardea herodias*)				
	Great Egret (*Ardea alba*)				
	Snowy Egret (*Egretta thula*)				
	Cattle Egret (*Bubulcus ibis*)				
	Green Heron (*Butorides virescens*)				
	Black-crowned Night-Heron (*Nycticorax nycticorax*)				

a. A California Bird Species of Special Concern (Shuford and Gardali 2008).

b. For Greater White-fronted Goose, only the Tule subspecies (*A. a. elgasi*) is considered a California Bird Species of Special Concern; for Song Sparrow, only the Suisun subspecies (*M. m. maxillaris*) and Modesto population (*M. m. mailliardi*) are considered California Bird Species of Special Concern.

c. A species listed as Threatened under the California Endangered Species Act (CDFW 2021).

from a survey location, but the survey area was limited to a selected agricultural field or wetland unit. To limit the influence of diminishing detection probability with distance from the survey location, counts were limited to the area within a 200-m-radius semicircle arc from the survey location, truncated by any field edges. (See Shuford et al. 2019 for additional details on survey design and field methods.) Because the total number of surveys conducted at each survey area varied, we included in this analysis only areas that were surveyed at least four times during a specific season, and, as an index of survey effort, we used GIS to map the specific survey area at each location and calculate the total area surveyed multiplied by the total number of surveys conducted during the season. The final data set included a total of 7,820 surveys from 504 unique locations within the Delta and the immediate surrounding area, with 4,067 surveys from 265 survey locations in the fall and 3,767 surveys from 504 survey locations in the winter.

Because of the large number of waterbird species detected, the original analysis grouped species based on similar habitat requirements, foraging style, and diet (Shuford et al. 2019). Here, we prioritized the analysis of six waterbird groups, representing 46 total species, that were of interest for conservation because of their special status or role in conservation-planning efforts (e.g., CVJV 2020) and/or were very common in the data set during at least one season (Table 1). Five of the six groups were commonly detected in both seasons, but we did not attempt to fit distribution models for diving ducks during the fall season because of their relatively low prevalence (proportion of survey locations at which they were detected). In addition, for cranes and geese in the fall, which primarily represented arriving migrants, we defined a truncated fall season that excluded surveys before September 23, after which they were more consistently detected. As with the riparian landbirds, we considered a waterbird group to be present (1) in a survey area during a given season if it was ever detected on any of the surveys during that season, and absent (0) if it was never detected. As an index of the relative abundance of the group at each location during each season, we calculated the total count of individuals across all surveys.

Distribution Modeling

We developed distribution models to identify predictive relationships between local- and landscape-scale covariates and the probability of the presence of each bird species or group. We developed these models using boosted regression trees, an approach that uses machine- learning algorithms which can identify complex non-linear interactions among predictors without requiring any prior assumptions about the form of those relationships (Elith et al. 2008). For each riparian landbird species, we developed models that represented their distribution during the breeding season. For each waterbird group, we developed separate models that represented their distributions during each of the fall and winter seasons. All models included presence/absence at each survey location as the response variable, survey effort as a predictor, and weights for each location based on the abundance index (Yu et al. 2020), reflecting increased confidence that survey locations with higher abundance provide the most suitable habitat (VanDerWal et al. 2009). For riparian landbirds, for which abundance indices at each survey location (a_s) ranged from 0 to 8, the weight at each survey location (w_s) was calculated as:

$$w_s = \sqrt{a_s + 1} \tag{1}$$

such that locations where we observed eight individuals were given three times as much weight as locations where we observed 0 individuals. For waterbirds, for which the abundance indices ranged from 0 to 8,174, the weight at each survey location was instead calculated as:

$$w_s = ln(a_s + 2) \tag{2}$$

such that areas within which we observed 1,000 individuals were given approximately ten times as much weight as areas where we observed 0 individuals.

Other predictors included a suite of metrics that represented the landscape at each survey location. Because the probability of species or group presence is likely to be influenced by the surrounding landscape on multiple spatial scales (Seavy et al. 2009; Reiter et al. 2015; Shuford et al. 2016), we included as predictors local metrics (which represented the area within which the bird survey took place) and landscape metrics (which represented the broader surrounding area), derived from a combination of field observations during the bird surveys and remotely-sensed data. We assumed there was relatively little change in the land-cover predictors relevant to riparian landbirds over the 2011 through 2019 survey period, and we developed one land-cover data set to represent the entire survey period. In contrast, we expected waterbird distributions to be influenced by the highly dynamic distribution of surface water and crop classes suitable for waterbird habitat, and we matched these predictors to the year and season in which each survey was conducted.

Riparian Landbird Models

To represent land cover at riparian survey locations in the Delta and throughout the Central Valley, we primarily relied on two recent sources of published land-cover data. The first was based on classification of imagery of the Delta in 2016 from the National Agriculture Imagery Program (NAIP) combined with detailed crop-cover data based on imagery from 2014 (Schwenkler 2019). However, many agricultural fields were fallowed in 2014 during drought conditions, and perennial crops have continued to expand in the region (DPC 2020). Thus, to better align this imagery with the bulk of our riparian landbird surveys in this region, we overlaid more recent crop-cover data based on imagery from 2018 (CDWR 2021). The second land-cover data set was based on classification of NAIP imagery for the Great Valley Ecoregion in 2009, 2012, and 2014 (Schwenkler 2018), which aligned well with the timing of the bulk of the surveys outside the Delta in 2012 and 2013. These data included polygons labeled as unspecified agricultural land, so we assigned crop-cover types according to imagery from 2014 (CDWR 2020). We grouped land cover classifications into a smaller set of major land cover classes likely to be relevant to riparian landbirds. Because riparian landbirds are frequently associated with specific types of riparian vegetation (Nur et al. 2008; Dybala et al. 2017), we also identified several riparian subclasses. We based these riparian subclasses on the U.S. National Vegetation Classification System (*https://usnvc.org*; see Appendix A, Table A1, which shows how California Wildlife Habitat Relationships and NVCS classifications were grouped into the land-cover classes and subclasses used in these models). In addition, we drew on additional sources of wetland data (Petrik et al. 2014; USFWS 2018) to distinguish permanent/semi-permanent nontidal managed wetlands as a wetland subclass of interest because they may have a distinct vegetation structure and more reliable water during the breeding season compared to other wetlands.

As candidate predictors of species presence, we summarized the landscape that surrounded each riparian survey location as the proportion of land that each class and subclass covered within circular buffers of two sizes: a 50-m radius (0.8 ha), which represented the local area within which the survey was conducted, and a 2-km radius (1257.6 ha), which represented the broader surrounding landscape. Although 2 km is a relatively large distance to consider for most landbird studies (Seavy et al. 2009), effects on this spatial scale have previously been found (Hostetler and Holling 2000; Hostetler and Knowles–Yanez 2003; Pennington and Blair 2011), including in riparian landbirds in California (Gardali and Holmes 2011). In addition, this scale provided more information about the surrounding landscape than predictor variables derived for smaller buffer sizes, which were often highly correlated with predictors that represented the local 50-m scale. All riparian landbird models included land-cover predictors on both the local (50-m) and landscape (2-km) scales.

Because the riparian landbird surveys were distributed over a relatively large spatial extent, we also included additional predictors that represented variation in the landscape and environment informed by previous distribution modeling efforts for riparian landbirds (Point Blue Conservation Science c2020). These included region (a categorical predictor that labeled whether the survey location was located north of the Delta in the Sacramento Valley region or not), climate variables, and the distance to the nearest stream. We obtained recent average climate data (1970– 2000) from WorldClim (*http://www.worldclim.com/version2*) with a resolution of 30 seconds of a latitude/longitude degree (approximately 1 km^2; Fick and Hijmans 2017), and we extracted annual mean temperature and total annual precipitation for each survey location. To estimate stream distance, we compiled spatial data from the National Hydrography Dataset (USGS 2020) representing the network of streams and rivers in the Central Valley and calculated the distance (m) to the nearest feature from each survey location. To limit the influence of a few large distances, we used the square root of this value as a predictor in the models.

Waterbird Models

To represent the local conditions within each waterbird survey area, we used field observations from each survey of the land-cover class surveyed (a categorical predictor) and the proportion of the survey area that was flooded. To represent the surrounding landscape—and particularly the highly dynamic distribution of surface water and crop classes that can provide suitable waterbird habitat—we relied on the USDA's National Agricultural Statistics Service's (NASS) Cropland Data Layer data specific to each year of the waterbird survey (2013–2014; NASS 2018) paired with remotely-sensed surface water data specific to the year and season of each waterbird survey from Point Blue Conservation Science's Water Tracker (*https://pointblue.org/watertracker*) (Reiter et al. 2018; Shuford et al. 2019). We grouped the original NASS land-cover classifications into a smaller set of classes likely to be relevant to waterbirds (see Appendix B, Table B1 which shows how NASS classifications were grouped into the land-cover classes used in these models), and, where the NASS classification indicated double-cropping, we retained the winter crop classification for use with the winter waterbird distribution models. As we did for the riparian landbirds, we again drew on an additional source of wetland data (Petrik et al. 2014) to identify managed wetlands as a distinct wetland subclass.

We represented the landscape that surrounded each waterbird survey area as the total area of each of these land-cover classes and the average proportion of each land-cover class that had surface water during each season, summarizing each of these statistics within circular buffers of three sizes: a 2-km radius (1257.6 ha), a 5-km radius (7,854.0 ha), or a 10-km radius (31,415.9 ha). Each of these scales has been found to be important to various waterbird species and groups (Elphick 2008; Reiter et al. 2015; Shuford et al. 2016); and thus, for each waterbird group, we considered three alternative sets of models that paired predictors representing the local survey area (land-cover class and proportion flooded) with landscape-scale predictors on one of these three scales (2 km, 5 km, or 10 km). Finally, we also included the distance to winter nighttime roosts as a predictor for the distribution of cranes, which have strong roost-site fidelity and have been shown to forage within 2 to 5 km of these locations (Ivey et al. 2015). We used spatial data that represented winter nighttime roost locations mapped from 2007 through 2009 (Ivey et al. 2016), with additions to this dataset made by The Nature Conservancy (The Nature Conservancy and G. Ivey, 2015, see “Notes”).

Model Fitting

We fit all models in R (R Core Team 2021) using the R packages ‘dismo’ and ‘gbm’ (Greenwell et al. 2020; Hijmans et al. 2020). Following Elith et al. (2008) and using the gbm.step function in the R package ‘dismo,’ we used cross-validation to train and test our models, as well as to optimize the number of trees, learning rate (the weight of each tree to the model; from the range 0.01, 0.005, 0.001, or 0.0005), tree complexity (the number of nodes in each tree; range 1–4), and bag fraction (the proportion randomly drawn from the training data; 0.5 or 0.75) to be used for each model. To enforce spatial separation of training and testing data and reduce spatial auto-correlation in the model residuals, we also used the ‘blockCV’ package to assign survey locations to spatial blocks (Valavi et al. 2019), and then randomly assigned entire spatial blocks to cross-validation folds (Roberts et al. 2017). For riparian species, we considered either 1-km or 2-km spatial blocks distributed among ten cross-validation folds, because these block sizes captured clusters of adjacent point count survey locations well. For waterbird groups, we considered either 8-km or 10-km spatial blocks distributed among five cross-validation folds, because these block sizes were closely aligned with the initial clustered sampling design using islands and tracts (Shuford et al. 2016).

For each species and group, we fit models with one of the spatial block sizes and—for waterbirds—landscape predictors on one of the three scales, and we ultimately selected the model with the best performance. The best-performing models were those that resulted in at least 1,000 trees and no more than 10,000 trees fit (Elith et al. 2008); did not have statistically significant spatial auto-correlation in the residuals (Moran’s $I > 0.05$; Dormann et al. 2007); and otherwise minimized deviance and maximized the cross-validated area under the receiver operating characteristic curve (AUC), which quantifies how well predictions discriminate observed presences from observed absences (Hanley and McNeil 1982). For riparian landbirds, 1-km spatial blocks performed best for five species (Black-headed Grosbeak, Common Yellowthroat, Nuttall’s Woodpecker, Song Sparrow, and Spotted Towhee) and 2-km blocks for the remaining four species (Ash-throated Flycatcher, Lazuli Bunting, Yellow Warbler, and Yellow-breasted Chat). For waterbird groups,10-km spatial blocks performed best in the fall and 8-km in the winter. However, to eliminate spatial auto-correlation for winter models for geese and cranes, we ultimately randomly assigned individual survey locations—rather than entire spatial blocks—to cross-validation folds. In addition, to eliminate spatial auto-correlation for Song Sparrow, we ultimately excluded survey locations north of the Delta, where the species is rare and there were very few detections. None of the final models had statistically significant spatial auto-correlation in the residuals.

Projected Distributions

We used the final models for each species and group to project their probability of presence across the current Delta landscape, again using the most recent land-cover data for the area within the legal Delta boundary (Schwenkler 2019), modified to include more recent, detailed crop-cover data from 2018 (CDWR 2021), as described in the "Riparian Landbird Models" section. We used the main summer crop-cover data to project the distributions of riparian landbirds during the breeding season and waterbirds during the fall season. For waterbirds during the winter season, we overlaid any distinct winter crop cover data for agricultural fields that were double-cropped (CDWR 2021). Projections of waterbird group presence also required estimates of open surface water, and we used the mean probability of open surface water during the fall and winter seasons, 2013–2019, derived from Point Blue Conservation Science's Water Tracker (Reiter et al. 2018).

From these representations of the current Delta landscape, we generated the necessary predictors to fit the final distribution models for each riparian landbird species and each waterbird group in each season. For waterbird groups, because land-cover class within each survey area was a categorical predictor included in each model, we only projected the probability of presence for pixels that represented the classes surveyed in each season. Unsurveyed land-cover classes have an unknown probability of waterbird group presence, including potentially suitable classes such as fallow fields, other wetlands, and permanent open water. However, we refined the projections for each waterbird group by assuming zero probability of presence for land-cover classes we had defined as incompatible with open-water habitat for waterbirds a priori, including perennial crops, and urban and barren land-cover classes in both seasons (CVJV 2006; Shuford and Dybala 2017; Peterson et al. 2020). For riparian landbirds, surveys were not limited to specific land-cover classes, and thus we projected the probability of riparian landbird species presence across the entire Delta landscape. However, we also refined the riparian landbird projections by assuming zero probability of presence in permanent open water, which we defined as unsuitable a priori.

Spatial Prioritization

Using the projected probability of presence for each species and group generated from the distribution modeling process, we used Zonation 5 software (Moilanen et al. 2022, *https://zonationteam.github.io/Zonation5/*), which uses spatial prioritization algorithms to identify the areas of the current Delta landscape most important to protecting and maintaining these bird communities. To reflect their distinct seasonal habitat and conservation needs, we conducted separate prioritization analyses for riparian landbirds, waterbird groups in fall, and waterbird groups in winter. Because the distributions of these species and groups are not limited to the Delta, and objectives and priorities for the conservation of each of these individual bird species or groups have not been defined for the Delta, we sought to identify the pixels with the highest overall value for bird conservation. Thus, for each prioritization analysis, we gave each species or group equal weight, and we used the CAZ1 variant of the Core Area Zonation algorithm, which does not necessarily ensure good coverage for each individual species or group, but rather emphasizes the pixels that provide high average coverage across all species or groups considered.

We defined Priority Bird Conservation Areas for riparian landbirds and waterbirds (in either season) as the pixels that ranked in the top 5% from each analysis. To further inform conservation strategies in the Delta and evaluate the vulnerability of these Priority Bird Conservation Areas to changes in land cover or use, we estimated the proportion of these pixels that fell within (1) major land-cover classes; (2) existing protected areas and and conservation easements (CCED 2022; CPAD 2022); (3) any of the six Priority Habitat Restoration Areas (DSC 2022); or (4) areas with a high (18% to 65%) or very high (>65%) risk of flooding over 10 years from projections of sea level rise for 2050 (DSC 2021).

We assumed that areas most vulnerable to changes in land cover or land use would include areas in agricultural land-cover classes, not protected, not within Priority Habitat Restoration Areas, and/or at high or very high risk of frequent flooding with sea level rise.

RESULTS

Survey Data

The nine riparian landbird species and six waterbird groups varied in their prevalence (the proportion of survey locations at which they were detected) and in their abundance indices (Table 1). The prevalence of riparian landbird species across survey locations throughout the entire Central Valley ranged from a low of 0.04 for Yellow-breasted Chat to a high of 0.83 for Spotted Towhee, and it was lower within the Delta for all species except Common Yellowthroat and Song Sparrow. Among the six waterbird groups, herons/egrets had the highest prevalence in both seasons (fall: 0.55; winter: 0.32) but also the lowest abundance indices at any one location, meaning they were widespread across survey locations but in relatively low numbers. In contrast, geese, dabbling ducks, and shorebirds all had lower prevalence but higher abundance indices, meaning they were more concentrated in fewer locations.

The model predictors that described the landscape surrounding the 716 unique riparian landbird survey locations and 504 unique waterbird survey locations indicated a diverse set of survey locations. For the riparian survey locations, there was a wide range in climate variables, distance from stream channels, and the proportion of the landscape made up of each land-cover class within both 50 m and 2 km of each survey location (Table A2). The land-cover classes within the waterbird survey areas were, by design, limited to alfalfa, irrigated pasture, rice, and managed wetlands during the fall, and these same land-cover classes plus corn and winter wheat during the winter. However, the landscape that surrounded these survey areas within 2 km, 5 km, and 10 km also included a wide range of land-cover classes (Table B2).

Model Performance

The cross-validated area under the receiver operating characteristic curve (AUC) of the final models ranged from 0.747 to 0.897 for riparian landbird species, and from 0.705 to 0.978 for waterbird groups, all exceeding the threshold of 0.7 generally considered adequate for modeling species distributions (Table 2; Swets 1988). We considered predictors with relative importance < 2% to be relatively uninfluential, and we report on predictors with higher relative importance scores.

Riparian Landbirds

Predictors describing the extent of riparian vegetation cover influenced the distributions of all nine riparian landbird species, and predictors describing the extent of wetland cover influenced the distributions of all but Yellow-breasted Chat. (Table A2). Distance to the nearest stream channel was influential for all but Spotted Towhee and Song Sparrow. Of these species, the probability of species presence was higher closer to stream channels for all but Nuttall's Woodpecker and Ash-throated Flycatcher; as the two cavity-nesting species, both had a higher probability of presence at intermediate distances (approximately 25 to 200 m). All nine species were also influenced by one or both climate variables. Total annual precipitation—a variable with a strong north-south gradient in the Central Valley (Fick and Hijmans 2017)—strongly influenced Song Sparrow, such that they were less likely to be present in locations with an annual precipitation over approximately 450 mm.

Average annual temperatures were lower in the Delta compared to the rest of the Central Valley survey locations; Common Yellowthroat and Spotted Towhee were more likely to be present in these cooler locations, whereas Ash-throated Flycatcher and Yellow-breasted Chat were more likely to be present in warmer locations. Finally,

Table 2 Model parameters and AUC scores from the final boosted regression tree models. (**A**) Riparian landbird species during the breeding season. (**B**) Waterbird groups in both fall and winter seasons. Also shown is the spatial scale of the predictors included. All riparian landbird models included predictors representing the surrounding landscape within 2 km, whereas for waterbird groups, predictors representing 2-km, 5-km, and 10-km scales were considered (*see text for details*).

Species	Season	Predictor Scale	Tree complexity	Learning rate	# Trees	AUC
A. Riparian landbird species						
Nuttall's Woodpecker	Breeding	2 km	4	0.005	1850	0.78
Ash-throated Flycatcher	Breeding	2 km	1	0.01	1400	0.80
Black-headed Grosbeak	Breeding	2 km	3	0.005	1050	0.80
Lazuli Bunting	Breeding	2 km	4	0.001	2700	0.76
Common Yellowthroat	Breeding	2 km	3	0.005	1450	0.75
Yellow Warbler	Breeding	2 km	1	0.005	1300	0.76
Spotted Towhee	Breeding	2 km	1	0.005	3750	0.90
Song Sparrow	Breeding	2 km	4	0.005	1050	0.87
Yellow-breasted Chat	Breeding	2 km	3	0.001	2700	0.84
B. Waterbird groups						
Geese	Fall	10 km	4	0.005	1050	0.95
	Winter	5 km	1	0.005	2800	0.90
Dabbling ducks	Fall	2 km	3	0.001	4350	0.96
	Winter	10 km	4	0.001	4650	0.98
Diving ducks	Fall	– insufficient data –				
	Winter	10 km	1	0.01	1050	0.98
Cranes	Fall	5 km	1	0.01	1300	0.94
	Winter	5 km	3	0.001	4100	0.89
Shorebirds	Fall	2 km	1	0.005	1650	0.92
	Winter	5 km	1	0.01	1100	0.92
Herons/Egrets	Fall	5 km	3	0.0005	2400	0.71
	Winter	10 km	1	0.001	7150	0.74

region was an influential predictor for Black-headed Grosbeak and Lazuli Bunting, which had a higher probability of being present in the Sacramento Valley region north of the Delta than in the Delta or San Joaquin Valley to the south. However, as noted above, there was also a strong regional pattern for Song Sparrow, which was largely absent from the survey locations in the Sacramento Valley.

The combined influences of these predictors on each of the nine riparian landbird species resulted in distinctly different predicted distributions across the Delta (Figure A1). Nuttall's Woodpecker, Ash-throated Flycatcher, and Black-headed Grosbeak are all species expected to be associated with mature riparian forest (Dybala et al. 2017), and all three species were predicted to have a high probability of presence along rivers near the perimeter of the Delta. In contrast, Common Yellowthroat, a species more associated with wetlands and riparian scrub, was most likely to be present in the central Delta and Yolo Bypass.

Waterbirds

In both fall and winter seasons, the most influential predictor of the distributions of most waterbird groups was the proportion of the survey area that was flooded, including all but herons/egrets during the fall, and cranes in both seasons (Table B2). Several groups were also influenced by the land-cover class of the survey area, as well as the interaction between land-cover class and the proportion of the survey area that was flooded. During the fall, dabbling ducks were most likely to be present in flooded managed wetlands, and shorebirds were most likely to be present in flooded managed wetlands and irrigated pasture. During the winter, geese and diving ducks were most likely to be present in flooded managed wetlands and corn, while herons/egrets were most likely to be present in flooded managed wetlands and rice. In both seasons, cranes were more likely to be present closer to nighttime roost sites.

Most of the remaining predictors that described the total area of different land covers that surrounded the survey area and the proportion of each that were flooded also had at least a small influence (relative importance > 2%) on the distributions of one or more groups in either season. We also found that of the three spatial scales we considered (2-km, 5-km, and 10-km radius), different scales performed best across groups and seasons (Table 2). In the fall, the landscape within 2 km best explained the distribution of dabbling ducks and shorebirds, within 5 km fit best for cranes and herons/egrets, and within 10 km fit best for geese. In the winter, the distributions of shorebirds, cranes, and geese were best explained by predictors that described the landscape within 5 km, whereas 10 km fit best for dabbling ducks, diving ducks, and herons/egrets. Using the best-performing spatial scale for each group and season, we found that the influence of the local- and landscape-scale predictors varied by group and season; none were universally influential (Table B2).

The predicted fall distributions of dabbling ducks, shorebirds, and herons/egrets, which were based on surveys as early as July 15, likely represented both the post-breeding dispersal of some locally-breeding species and the arrival of migrants that winter in the Delta or use the Delta as a stop-over site during fall migration. Consequently, their predicted fall distributions were relatively diffuse and included high probabilities of presence in the northwestern areas of the Delta, especially along the Yolo Bypass, where extensive wetlands and irrigated pasture can provide suitable habitat (Figure B1). In contrast, the predicted fall distributions of crane and geese groups, which were based on the truncated fall season we defined as beginning September 23, after which they were more consistently detected, primarily represented arriving migrants and were concentrated in the central Delta. However, we note that predictions for the presence of each group in the corn land-cover class, also concentrated in the central Delta, were excluded because of the limited sampling of harvested corn fields in the late fall. Both cranes and geese forage on the waste grain in corn fields after harvest, and are thus using corn in the late fall season in addition to other suitable land-cover classes. The predicted distribution of cranes in the fall also reflected the strong influence of distance from their nighttime roosts, which are also concentrated in the central Delta.

For the winter season, we were able to predict the probability of waterbird group presence over a larger proportion of the Delta, including the corn-dominated central Delta (Figure B2). Compared to their fall predictions, dabbling ducks continued to have a high probability of presence in the wetlands of the Yolo Bypass, but also had a high probability of presence in postharvest-flooded corn fields and wetlands of the central Delta. Shorebirds and geese had a spatial distribution similar to that of dabbling ducks, but geese were more concentrated in the central Delta, and shorebirds had a lower overall probability of presence. The distribution of herons/egrets was predicted to be more widespread throughout the Delta but with a relatively low probability of presence throughout, perhaps reflecting their use of both flooded and non-flooded land covers. Cranes were again predicted to have their highest probability of presence in the central Delta near their nighttime roosts and in areas with flooded corn and rice. While we did not model the distributions of diving ducks in the fall, their distribution during winter was the most restricted of any group, with most observations concentrated in wetlands and flooded corn. However, we again note that diving ducks in the Delta also use the deep rivers, sloughs, and channels that were not included in the waterbird

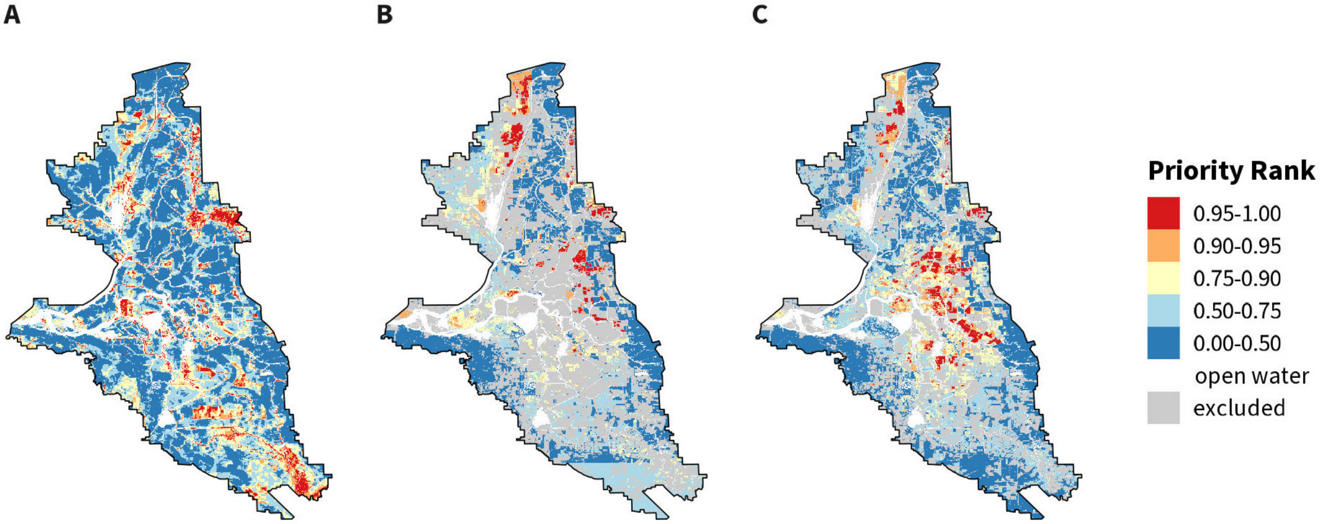

Figure 2 Results of spatial prioritization analysis for (**A**) riparian landbirds during the breeding season, (**B**) waterbirds during the fall season, and (**C**) waterbirds during the winter season. Results indicate the relative priority rank of pixels across the Delta landscape for conserving all species or groups, with the highest priority pixels shown in *red* and the lowest in *blue*. Areas excluded from prediction are shown in *gray*. To aid in orientation, open water is shown in *white*.

surveys and thus were excluded from these predicted distributions.

Spatial Prioritization

The most valuable areas of the Delta for supporting all nine riparian landbird species during the breeding season were distributed along the Sacramento, San Joaquin, Cosumnes, and Mokelumne rivers, as well as along the Yolo Bypass and within the central Delta (Figure 2). The most valuable areas for supporting all six waterbird groups were concentrated along the Yolo Bypass and in the central Delta for both the fall and winter seasons. From these results, we identified a combined total of 26,019 ha of Priority Bird Conservation Areas for riparian landbirds during the breeding season and waterbirds during either the fall or winter, defined as the top 5% of pixels from each spatial prioritization analysis (Figure 3). Approximately 601 ha (2.3% of the total) ranked among the top 5% for both riparian landbirds and waterbirds, of which we estimated 87% were protected, 83% were wetlands, and <1% were located in areas projected to be at high risk of annual flooding with sea level rise (Table 3). Considering all 26,019 ha together, we estimated that 39% fell within existing protected areas or conservation easements, 28% within one of the six Priority Habitat Restoration Areas, and 18% in areas at high or very high risk of annual flooding under projections of sea level rise by 2050. By land-cover class, they were overwhelmingly represented by four groups, evenly split among them: wetlands (24%), riparian (23%), corn (23%), and all other agricultural lands (23%). However, considering protected status by land-cover type, the majority of the priority riparian (63%), corn (70%), and other agricultural lands (84%) were unprotected, while 21% of the priority wetlands remained unprotected.

DISCUSSION

Bird conservation is a core component of meeting goals for the Delta ecosystem, and is likely to benefit bird populations well beyond the boundaries of the Delta. Here, we capitalized on thousands of bird surveys to produce detailed, comprehensive representations of the current distributions of riparian landbird species and waterbird groups throughout the Delta, providing insights into the specific locations within the Delta that currently provide the most bird conservation value for each bird group and season

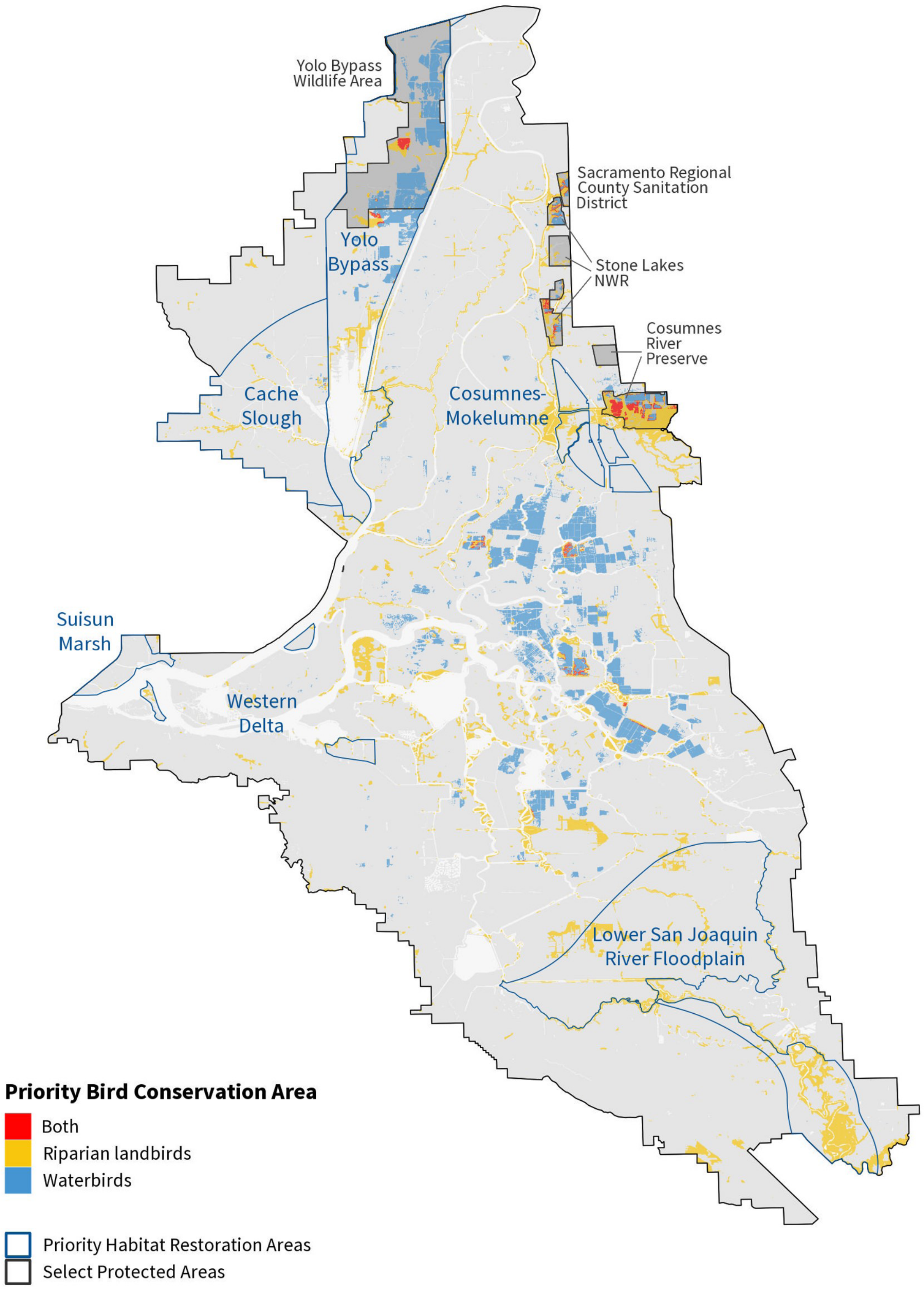

Figure 3 Priority Bird Conservation Areas identified for riparian landbirds and waterbirds, highlighting areas of overlap. Also shown are the six Priority Habitat Restoration Areas (labeled with *blue text*) and four Select Protected Areas (labeled with *gray text*). To aid in orientation, open water is shown in *white*, and the remainder of the Delta is shown in *gray*.

Table 3 Characteristics of the Priority Bird Conservation Areas identified for riparian landbirds, waterbirds in either season, or both, including the total area (ha) and the total area (and %) falling within protected areas and conservation easements (CCED 2022; CPAD 2022), within Priority Habitat Restoration Areas (Delta Stewardship Council 2020), or within areas that have a high risk of flooding under projected sea level rise by 2050 (Delta Stewardship Council 2021). Also shown are the total area (and %) falling within one of the three most common land-cover classes (wetlands, riparian, or corn) or all other agriculture.

	Total		Riparian landbirds		Waterbird groups		Both	
Total area (ha)	26,019		14,920		11,700		601	
Protected areas & conservation easements	10,254	(39%)	4,983	(33%)	5,794	(50%)	523	(87%)
Priority Habitat Restoration Areas	7,306	(28%)	4,541	(30%)	2,878	(25%)	113	(19%)
High flood risk with sea level rise	4,669	(18%)	3,436	(13%)	1,206	(5%)	27	(<1%)
Landcover								
Wetland	6,133	(24%)	2,368	(17%)	3,264	(29%)	501	(83%)
Riparian	5,925	(23%)	5,925	(41%)	0	(0%)	0	(0%)
Corn	5,984	(23%)	991	(7%)	4,959	(45%)	34	(6%)
All other agriculture	6,100	(23%)	3,157	(22%)	2,877	(26%)	66	(11%)

(Figure 2). There were some overlaps between the Priority Bird Conservation Areas identified for riparian landbirds and waterbirds, the majority of which was protected (Table 3), including the Cosumnes River Preserve, Stone Lakes National Wildlife Refuge, restored bufferlands surrounding the Sacramento Regional County Sanitation District, and the Yolo Bypass Wildlife Area and nearby conservation easements (Figure 3). Our results indicated the success of these protected areas and easements in providing valuable habitat for both riparian landbirds and waterbirds, and that continued protection and effective management of these areas is a critical strategy for conserving riparian landbirds and waterbirds in the Delta. In addition, of the total 26,019 ha of Priority Bird Conservation Areas, approximately 28% fell within one of the Delta's Priority Habitat Restoration Areas (Table 3), providing insights into strategic areas where restoration could expand existing patches of particularly valuable habitat; riparian landbird priorities were distributed among each of the Priority Habitat Restoration Areas, whereas waterbird priorities fell entirely within the Yolo Bypass and Cache Slough (Figure 3), providing insights into strategic areas where restoration could expand existing patches of particularly valuable habitat.

The dynamic nature of land cover in the Delta means that these highest-priority areas are not necessarily fixed locations, especially for the more than 60% that are not currently protected (Table 3), including the majority of the priority areas identified in riparian, corn, and other agricultural land covers. Our results align with previous studies that have demonstrated the success of agricultural land in the Delta and broader Central Valley in providing valuable habitat for waterbirds and that have expressed concerns about the vulnerability of these lands to conversion to other, less bird-friendly land-cover classes (Ivey et al. 2015; Shuford and Dybala 2017; Shuford et al. 2019; Dybala et al. 2020). For example, in recent decades, corn has been one of the most common crops in the Delta by acreage, but declined by more than 10,000 acres (22%) between 2009 and 2016; over the same period, the extent of perennial crops—a land-cover class considered incompatible with waterbird habitat (CVJV 2006; Shuford and Dybala 2017; Peterson et al. 2020)—grew by more than 10,000 acres each for almonds and wine grapes (401% and 38%, respectively; DPC 2020). Climate change may also reduce yields of corn and other crops, further incentivizing farmers to switch to higher-revenue perennial crops (DSC 2021). Simultaneously, 18% of the total priority area was at a high or very high risk of annual flooding by 2050 with in weighting schemes, which gaps in data need to be filled, and whether identifying the top 5% to protect and manage will be sufficient to meet conservation goals.

CONCLUSIONS

The results of these analyses represent the most current state of the science on the distributions of riparian landbirds and waterbirds across the Delta and the areas with a high confidence of importance to bird conservation, but they are not the final word on bird conservation priorities and strategy within the Delta's evolving landscape. Our predictive models and approach to spatial prioritization provide a framework that can support collaborative efforts to define bird-conservation priorities and objectives, including additional bird species. Our models can also be used to project how bird communities will respond to future changes in the Delta's landscape, allowing bird communities to be included in a Multiple Benefit Conservation framework to identify synergies and trade-offs (sensu Gardali et al. 2021) with other projected effects of future landscape change (Dybala et al. 2019; Gardali et al. 2021). These analyses help fill a science need that will facilitate bird conservation and the long-term vision of a resilient Sacramento–San Joaquin Delta ecosystem.

DATA AVAILABILITY

The final distribution model objects are available from Zenodo. *https://doi.org/10.5281/zenodo.7531945*

The land cover data (shown in Figure 1), spatial prioritization results (shown in Figures 2 and 3), and projected distributions for individual species and groups (shown in Figures A1, B1, and B2) are available from the California Department of Fish & Wildlife Biogeographic Information and Observation System (BIOS) [ds3038-ds3069]. *https://apps.wildlife.ca.gov/bios6/?bookmark=356.*

Additional environmental variables used to develop the distribution models and predicted distributions are available from Zenodo. *https://doi.org/10.5281/zenodo.7672193*

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