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Identifying habitat conservation priorities and gaps for migratory shorebirds and waterfowl in California

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Abstract Conservation of migratory shorebirds and waterfowl presents unique challenges due to extensive historic loss of wetland habitats, and current reliance on managed landscapes for wintering and migratory passage. We developed a spatially-explicit approach to estimate potential shorebird and waterfowl densities in California by integrating mapped habitat layers and statewide bird survey data with expert-based habitat rankings. Using these density estimates as inputs, we used the Marxan site-selection program to identify priority shorebird and waterfowl areas at the ecoregional level. We identified 3.7 million ha of habitat for shorebirds and waterfowl, of which 1.4 million ha would be required to conserve 50% of wintering populations. To achieve a conservation goal of 75%, more than twice as much habitat (3.1 million ha) would be necessary. Agricultural habitats comprised a substantial portion of priority areas, especially at the 75% level, suggesting that under current management conditions, large areas of agricultural land, much of it formerly wetland, are needed to provide the habitat availability and landscape connectivity required by shorebird and waterfowl populations. These habitats were found to be largely lacking recognized conservation status in California (96% un-conserved), with only slightly higher levels of conservation for priority shorebird and waterfowl areas. Freshwater habitats, including wetlands and ponds, were also found to have low levels of conservation (67% un-conserved), although priority shorebird and waterfowl areas had somewhat higher levels of conservation than the state as a whole. Conserving migratory waterfowl and shorebirds will require a diversity of conservation strategies executed at a variety of scales. Our modeled results are complementary with other approaches and can help prioritize areas for protection, restoration and other actions.

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Traditional habitat protection strategies such as conservation easements and fee acquisitions may be of limited utility for protecting and managing significant areas of agricultural lands. Instead, conservation strategies focused on incentive-based programs to support wildlife friendly management practices in agricultural settings may have greater utility and conservation effectiveness.

Keywords Pacific Flyway · Conservation planning · Marxan · Gap analysis · Waterbirds

Introduction

Migratory shorebirds and waterfowl have large-scale habitat needs that stretch the limits of conservation planning and implementation. Of the 31 species of shorebirds that winter in North America, 22 breed in arctic and subarctic regions (Page and Gill 1994). En route to and from their breeding grounds, most shorebirds and waterfowl refuel throughout a network of sites along major migration pathways.

Over the last two centuries, these migratory pathways and wintering areas have been greatly modified by humans. Destruction of wetlands and water diversions have reduced and degraded habitat availability at stopover and wintering sites (Page and Gill 1994). In California, over 90% of the state's historical two million hectares of wetlands has been lost (Dahl 1990). Large complexes of wetlands once supported some of the largest concentrations of wintering waterfowl and shorebirds in the world (Banks and Springer 1994). With large-scale conversion of wetlands to agricultural and urban uses, a smaller and more broadly-dispersed network of managed wetlands and flooded agricultural fields now fills the role of historic natural wetlands (Davidson and Evans 1986; Elphick 2000). A patchwork of wildlife refuges, duck clubs, nature preserves, and agricultural lands provides globally important migratory routes and wintering areas for millions of shorebirds and waterfowl (Heitmeyer et al. 1989; Shuford et al. 1998). Many of these areas are privately owned, however, and are vulnerable to conversion as a result of population growth and climate change. Thus, it is critical to apply regional and landscape perspectives in the protection and management of remaining stopover and wintering sites for migratory shorebirds and waterfowl (Skagen and Knopf 1993; Farmer and Parent 1997; Naugle et al. 2001).

Conservation planning for migratory waterfowl and shorebirds has traditionally been based on estimates of population numbers and changes over time. Recently, this has entailed the use of energetics models to estimate the amount of habitat of known quality needed to support populations of a desired size, especially in managed wetlands and agricultural landscapes (Reinecke and Loesch 1996; CVJV 2006). Shorebird and waterfowl conservation goals are generally expressed at the scale of regions (Brown et al. 2001; NAWMP 2004) or even watershed basins (CVJV 2006).

This broad-scale population-based approach differs from the spatially-explicit occurrence- or feature-based approach in systematic conservation planning and reserve design, where the goal is to efficiently maximize species or habitat representation and/or diversity (Williams et al. 1996; Margules and Pressey 2000). A common approach to reserve design is to identify feature- or species-specific conservation goals or targets—generally defined as a percent of the current total—and identify the set of lands with the lowest cost (or smallest area) that achieves those targets. Several computational approaches have been developed to address this problem (known as the minimum-set problem) (Pressey et al. 1997). For complex problems in which the spatial configuration of sites is important, Marxan (Possingham et al. 2000) is the most widely used.

A reserve design strategy based on species representation is appropriate for species that tend to be evenly distributed throughout well-mapped habitat types, and for sedentary species whose population occurrence is well known. However, for highly mobile species that use ephemeral habitats (e.g., shorebirds and waterfowl), habitat quality and species abundance may be more relevant for conservation planning than species representation. For these and other reasons, shorebirds and waterfowl typically have not been included in systematic reserve design exercises. However, Marxan and other packages are flexible enough to accommodate a variety of conservation goals and inputs. Using that flexibility, we developed a new hybrid approach, combining comprehensive population counts and field-based expertise to rank mapped habitats for shorebirds and waterfowl at the species level. We then used Marxan to identify a set of high-priority areas for conservation and restoration, and characterized conservation gaps in the resulting priority areas.

Our goals were to report spatial patterns of habitat use and the potential range of densities for shorebirds and waterfowl in California; to identify the highest priority areas for shorebird and waterfowl conservation; and to quantify the conservation status and land ownership characteristics of these priority areas.

Methods

Mapping waterbird habitats

Because of the broad range of shorebird and waterfowl habitat needs and the absence of a single source of statewide spatial data in which all of these habitats were well represented, we created a composite migratory waterbird habitat layer for California. We focused on the most common habitats used by shorebirds and waterfowl and cross-referenced classification schemes to integrate several high- to moderate-resolution geographic information system (GIS) datasets into one composite habitat layer.

Each data layer was converted to ArcInfo grid format at a resolution of 30 m $\times$ 30 m (900 m^2), clipped to the study area, and merged with other data layers in a sequence determined by a combination of map accuracy and specificity (Table 1). After merging the layers, we removed any habitat within the boundary of developed urban areas, as mapped in 2004 by the California Department of Conservation Farmland Monitoring and Mapping Program, to avoid over-estimating habitat availability. We resampled the final grid to a 100-m pixel (1-ha) resolution and removed isolated pixels that were unlikely to represent actual waterbird habitat. We also excluded agricultural habitats within coastal ecoregions, except those containing at least 10% natural or semi-natural wetlands (all non-agricultural habitat types except lakes) within a 5-km radius. This reflects the observed low importance of those agricultural lands for foraging shorebirds and waterfowl, except where they are associated with wetlands.

Estimating relative densities of shorebirds and waterfowl

Summarizing population counts by region

To capture large-scale variation in habitat use, we used regional population survey data to develop estimates of the potential density of shorebirds and waterfowl in each habitat type, stratified by region. For shorebirds, we used data from comprehensive shorebird counts

Table 1 Area of each waterbird habitat type mapped for the state of California

Habitat category	Habitat type	Data source(s)[a]	Total (ha)
Freshwater	Lake/reservoir (≥3 ha)	NHD	182,893
	Freshwater wetland	CDFG, NWI, U. Redlands	267,230
	Freshwater pond (<3 ha)	NHD, NWI	83,747
	Vernal pool grassland	Holland	380,013
Estuarine	Tidal marsh	NWI	15,163
	Tidal flat	NWI	34,688
	Subtidal estuary	NWI, CCM	102,673
	Eelgrass	CCM	8,823
Saline	Alkali playa/lakeshore	NWI	268,801
	Saline lake[b]	NHD	159,550
	Salt pond		14,353
Agricultural	Pasture	DWR	630,438
	Rice	DWR	232,555
	Grain and hay crops	DWR	348,608
	Idle cropland	DWR	68,823
	Field crops	DWR, SCAG	867,355

Agricultural types in coastal ecoregions were filtered based on their proximity to wetland habitats

[a] In order of precedence: *CCM* California Current Marine Ecoregional Plan (TNC internal), *Holland* R.F. Holland Central Valley Vernal Pool GIS, *NWI* National Wetlands Inventory, *NHD* National Hydrology Dataset, *U. Redlands* University of Redlands Salton Sea Digital Atlas, *DWR* Department of Water Resources County Land Use Survey Data, *CDFG* California Department of Fish and Game Central Valley Wetlands and Riparian GIS, *SCAG* Southern California Association of Governments Riverside County Land Use 2001

[b] Identified by W. David Shuford

conducted in wetland habitats along the Pacific Flyway from 1988 to 1995 during fall, winter, and spring (Shuford et al. 1998; Page et al. 1999). Temporal and spatial coverage varied by region, but within California all important wetland habitats were surveyed over at least 3 years, primarily by ground-based surveys except in the Central Valley, where aerial counts were also used. Migration surveys were conducted over one to 2 weeks in fall and in 1 week in spring. Because shorebirds may be mobile during winter, are very mobile during migratory periods and use a variety of habitats across large landscapes, surveys were intended to estimate regional population numbers, as well as numbers using specific known sites. For our analysis, we assigned count data to ecoregions adapted from Bailey (1995), except in the Central Valley, where we parsed data at the basin level to capture important geographic variation. The boundaries for the eight Central Valley basins were those delineated by the California Department of Water Resources, excluding Suisun Marsh, which was not surveyed for shorebirds. Hereafter, ecoregion divisions for the shorebird data include those for the Central Valley basins.

For waterfowl, we used data for California from 2000 to 2005 from the midwinter aerial surveys conducted by the U.S. Fish and Wildlife Service and the California Department of Fish and Game. The surveys are not intended to be comprehensive, but the standardized protocols facilitate comparison of relative population numbers across survey areas and years (Eggeman and Johnson 1989). Data from the seven survey areas within California were allocated to the most appropriate ecoregion, although boundaries were not always well-aligned. The largest discrepancy was the Sacramento—San Joaquin River Delta region, which was part of the San Francisco Bay survey area, but we allocated these data to the geographically appropriate Central Valley ecoregion.

We used data for only well-sampled species, excluding rare, uncommon, and vagrant species, and those associated primarily with habitats not (or poorly) covered by these surveys, namely sandy shoreline, rocky shoreline, rivers, and open ocean. Because the Pacific Flyway surveys were focused on wetlands, some species with non-wetland (e.g., upland agriculture and pasture) primary habitat associations were likely underestimated.

For each species, season (shorebirds only), and ecoregion we calculated the mean number of birds counted across years (Table 4 in Appendix). For shorebirds, because not all sites were surveyed each year, the count for an ecoregion was only included if large wetland areas (i.e., San Francisco Bay and the Salton Sea) were counted that year.

Ranking habitats by species

Because the shorebird and waterfowl population surveys were intended to be summarized over large geographic regions, our goal was to downscale these estimates to generate a finer spatial depiction of habitat use. Due to spatial limitations of the data, we were unable to employ traditional statistical modeling techniques to generate density predictions. Thus, rather than assuming a uniform distribution of birds across habitat types, we developed a quantitative approach for allocating densities across mapped habitats on the basis of expert knowledge of habitat preferences. This approach reflects data availability at the time of this study and was intended as an iterative process, with new density and distribution information to be used as it becomes available.

Shorebird and waterfowl experts (co-authors Page, Shuford, Stenzel, and Hickey; and N. Warnock), as a group, ranked habitat preferences for each species on the basis of predetermined mapped habitat types (Table 1). Habitats were ranked according to their potential to support high densities (rather than overall numbers) of a given species. We allowed the ranking of up to eight habitat types for each species, but in most cases many fewer types were included. For simplicity, habitat ranks were constant across seasons and ecoregions. However, rice may have been undervalued for some species (especially dabbling ducks) in this process. We attribute this to factors related to the shorebird surveys used for this analysis: (1) a lower prevalence of winter flooding practices (versus burning) during that time period and (2) a difficulty in distinguishing flooded rice fields from other flooded agricultural types during aerial surveys.

We then developed weighting schemes to allocate the total mean bird count by species in an ecoregion/season to available habitats in the order ranked. Our primary weighting scheme represented a relatively even weighting of habitats. Owing to high uncertainty in the relative importance of each habitat type, however, we also examined a more uneven weighting scheme as a simple sensitivity analysis. For simplicity, schemes were not unique to each species but were generated automatically based on the number of habitats over which each species was ranked, with weights summing to one for each scheme (Table 2).

The "even" weighting scheme was conservative in that it resulted in fairly even allocations of birds across habitats, with relatively small differences from one rank to the next. This minimized the influence of any one habitat, given the experts' uncertainty regarding the true relative importance of habitats. The "uneven" weighting scheme gave a great majority of the weight (between 0.72 and 1) to the highest ranked habitat, assuming that each species has a primary habitat preference that overshadows its use of other habitats.

Table 2 Habitat suitability weighting schemes used to allocate shorebird and waterfowl count data in California

Priority	Number of habitats							
	1	2	3	4	5	6	7	8
1	1	0.60	0.45	0.36	0.30	0.26	0.23	0.20
	1	*0.84*	*0.82*	*0.80*	*0.77*	*0.76*	*0.74*	*0.72*
2		0.40	0.30	0.27	0.24	0.21	0.19	0.18
		0.16	*0.12*	*0.09*	*0.08*	*0.08*	*0.07*	*0.07*
3			0.25	0.20	0.19	0.18	0.17	0.15
			0.06	*0.06*	*0.06*	*0.06*	*0.06*	*0.06*
4				0.17	0.15	0.15	0.14	0.13
				0.05	*0.05*	*0.05*	*0.05*	*0.05*
5					0.11	0.12	0.12	0.12
					0.04	*0.04*	*0.04*	*0.04*
6						0.08	0.10	0.10
						0.01	*0.03*	*0.03*
7							0.05	0.09
							0.01	*0.02*
8								0.03
								0.01

The proportions representing the "even" weighting scheme are on top of each cell; the "uneven" weighting proportions are shown below in italics. For each species, 1–8 habitat types were ranked by waterbird experts. Depending on the number of ranked habitats per ecoregion or Central Valley basin (columns), a different set of weights was used, adding up to 1 in each case

Mapping relative shorebird and waterfowl densities

For each weighting scheme, we assigned habitat preference weights for each study species and each ecoregion separately to ensure that weights totaled one for each species/area combination. Not all preferred habitats identified for a given species were mapped in all ecoregions in which it was encountered, so for each ecoregion, we adjusted the species-specific weightings on the basis of the habitats actually mapped. For example, if the top-ranked habitat for a species was not present in a given ecoregion, the #2 habitat became #1, and subsequent habitat rank values were each decreased by 1.

To allocate relative densities by species and habitat type, we divided the mean seasonal bird counts for each species and ecoregion by the number of hectares of each habitat type, weighted by its importance. For groups that were not identified to species (e.g., small sandpipers), we allocated counts in proportion to the species' representation among individuals identified to species. The densities (birds/ha) for ecoregion k, habitat j, and species s were calculated as $d_{j,k,s} = (N_{k,s} \cdot w_{j,s})/H_{j,k}$, where $N_{k,s}$ = mean number of individuals of species s (by season) in ecoregion k, $H_{j,k}$ = total area (ha) of habitat type j in ecoregion k, and $w_{j,s}$ = habitat suitability weight for habitat j and species s.

Habitat-specific densities were combined at the level of 1,000-ha hexagonal planning units (a total of 41,668 for the entire state), and then summed across species to obtain combined total density estimates (birds/1,000 ha) for shorebirds and waterfowl, as groups.

Shorebird densities were estimated for fall, winter, and spring, while waterfowl densities were only estimated for the winter season, based on data availability.

Given the approximate nature of the habitat rankings and weights, large temporal and geographic variability in waterbird habitat use, and substantial seasonal and annual variation in habitat availability, these mapped densities should not be treated as actual expected densities. Rather, they represent an approximation of the relative importance of different habitats and geographic regions for our study species. Given this approach, poorly mapped habitat types may have had artificially high relative densities, but this potential issue was minimized by aggregating relative densities at the level of 1,000-ha planning units and by excluding habitat-ecoregion combinations containing less than 10 ha of habitat.

Prioritizing waterbird habitats

Based on our estimated relative densities of shorebirds and waterfowl, we used the site-selection program Marxan (Possingham et al. 2000; Ball et al. 2009) to identify an efficient configuration of habitats based on specific goals. Marxan, which uses a heuristic simulated annealing algorithm, was developed to identify efficient, near-optimal spatial solutions to complicated conservation planning problems (Possingham et al. 2000). An important feature of this algorithm is spatial configuration, which is manipulated via a boundary length modifier (BLM) specifying the relative importance of spatial cohesiveness (versus minimum area) of the solution. Given the fragmentation of human-dominated landscapes containing shorebird and waterfowl habitats, we chose a low-intermediate BLM (0.1). This allowed small, isolated habitats to be included while favoring solutions with some cohesiveness, given the potential importance of wetland connectivity to shorebird and waterfowl foraging patterns (Farmer and Parent 1997; Naugle et al. 2001).

Our Marxan goals (or targets) were expressed as the percent of the mean number of birds per ecoregion (N_i) that would be protected given the conservation of a specific set of lands in their current condition (i.e., without restoration or additional water inputs). While conservation plans and implementation strategies call for population increases of many shorebird and waterfowl species via habitat restoration and improved management (CVJV 2006), our approach assumed constant densities and fixed habitat areas. Thus our conservation goals could not be greater than 100%, which would result in the selection of all areas with any mapped habitat value. We examined two goals, 50 and 75% of the total mean count of each study species in each ecoregion or basin (by season). These percentages should not be considered as actual population goals for the species, but as a way to prioritize areas for future planning or immediate conservation.

Population goals and relative density estimates were specified separately for each ecoregion to ensure that all priority areas were not in the same ecoregion, and that potential conservation areas were distributed across coastal and interior portions of California, which may contain distinct populations.

Three Marxan inputs were summarized for each 1,000-ha planning unit:

1. *Number of birds allocated based on survey data and experts' species-specific habitat rankings.* For waterfowl, we used winter numbers (the only season available). For shorebirds, we included fall, winter, and spring densities—estimated separately—to represent overall, cross-season habitat requirements. We also ran Marxan for shorebird winter numbers to compare with the waterfowl solution (excluding the Modoc Plateau ecoregion given the lack of coverage for shorebird surveys).

2. *Conservation goal, or percentage of population to be contained in conservation solutions.* We used two values for all ecoregions—50 and 75%—in order to compare habitat composition and efficiency across ecoregions and conservation goals.
3. *Suitability for conservation implementation.* We defined this solely as a function of housing density in year 2000 at the census-block level (Theobald 2005). Suitability cost weighting values ranged from 3,000 for suburban and urban areas (<0.69 ha per unit) to 1,000 for uninhabited areas. Because we assumed that rural development would be not be entirely incompatible with shorebird and waterfowl habitat use, exurban (0.7–16.2 ha per unit) and rural (>16.3 ha per unit) areas were assigned cost weightings of 2,000 and 1,200, respectively.

Using these inputs and settings, we executed ten Marxan runs to evaluate the number of times that each planning unit was selected in the resulting conservation solution. The units selected at least seven times were considered part of the solution for that conservation goal.

Analyzing conservation gaps

We conducted a gap analysis (Scott et al. 1993) to identify what percentage of priority shorebird and waterfowl areas in the solution already had some conservation status—defined as any land managed by local, state or federal agencies; and lands held in fee by conservation organizations, or via conservation easement by private or public entities (e.g., Natural Resource Conservation Service's Wetland Reserve Program). Gap analysis typically looks at the relative percentage of land use or vegetation types with different levels of conservation management or protection. For this assessment, we first quantified mapped waterbird habitats (Table 1) by general category (estuarine, saline, freshwater, and agricultural) and ownership class (federal, state, other public, private fee title, private easement, and other) statewide. We then repeated the calculation for the 75% solutions for shorebirds and waterfowl obtained from Marxan.

Results

Waterbird habitat

We identified nearly 3.7 million ha of potential waterbird habitat within California (Table 1). The most extensive habitat types were agricultural, with the largest area represented by field crops, followed by pasture, vernal pool grasslands, and grain and hay crops. Estuarine habitats, including eelgrass, tidal flat and tidal marsh, were among the most limited in spatial extent.

Habitat suitability rankings

Habitats were ranked for suitability with respect to 17 shorebird and 25 waterfowl species (Table 5 in Appendix). For waterfowl, freshwater wetland, sub-tidal estuary, eelgrass bed, salt pond, freshwater pond, and grain and hay crops were ranked as most suitable for one or more species. For shorebirds, saline lake, alkali playa/lakeshore, freshwater wetland, tidal flat, and pasture were ranked highest for at least one species.

Spatial habitat suitability

Using the "even" habitat weighting scheme, our expert-based habitat suitability rankings allocated the highest potential densities for fall, winter, and spring shorebirds to estuarine habitats—primarily tidal flats—along the coast (Fig. 1a–c). Potential densities were particularly high in the San Francisco Bay (Central Coast ecoregion). Inland, the Salton Sea

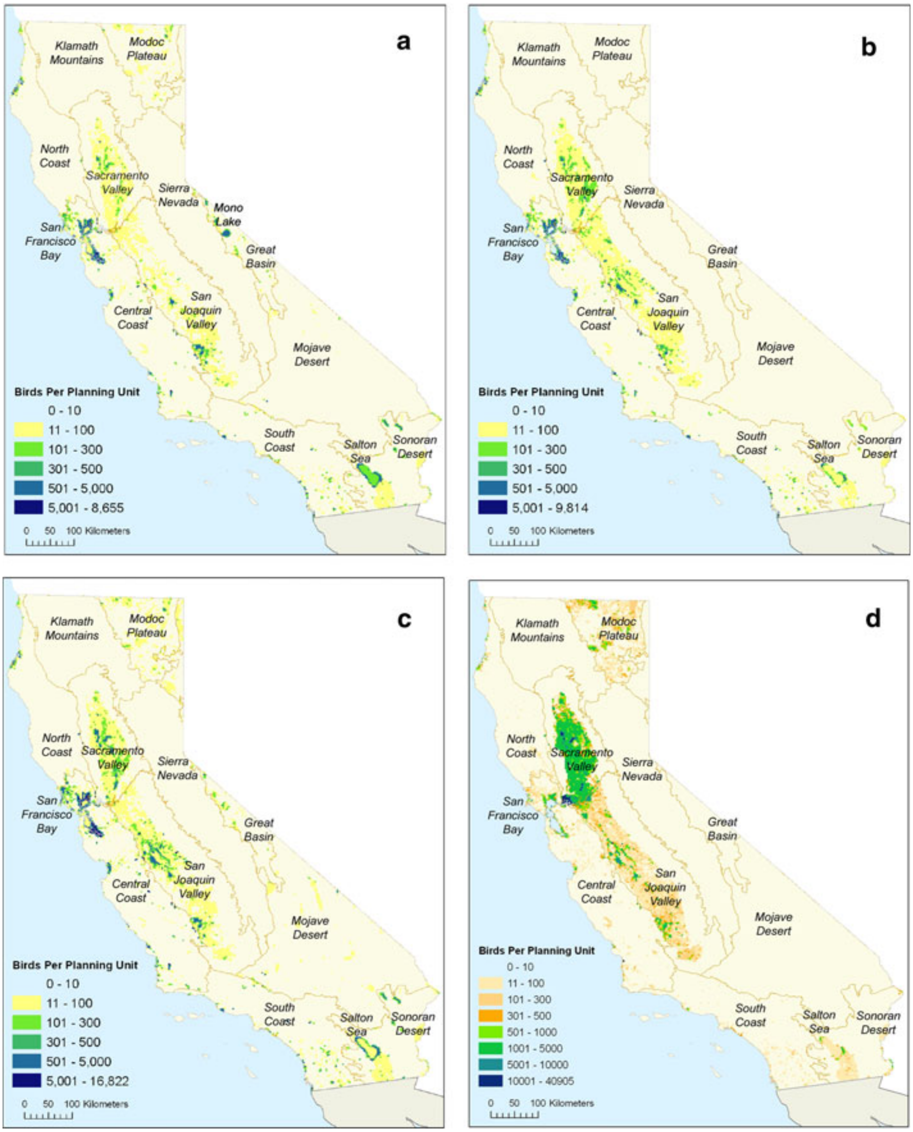

Fig. 1 Estimated potential densities in California for **a** fall shorebirds, **b** winter shorebirds, **c** spring shorebirds; and **d** winter waterfowl. All species (Table 5 in Appendix) were weighted equally, using an "even" habitat-weighting scheme (see Table 2)

(Sonoran Desert ecoregion) stood out as the single largest concentration of highly suitable shorebird habitat across seasons, especially in the fall (Fig. 1a), while Mono Lake (Great Basin ecoregion) also concentrated similar suitable habitat in the fall (Fig. 1a). Within the Sacramento Valley, San Joaquin Valley, and parts of the Modoc Plateau, and Sonoran Desert ecoregions, potential densities were low and broadly distributed across large agricultural landscapes, with clusters of higher densities allocated to freshwater wetland habitats.

Winter waterfowl habitat suitability using the "even" habitat weighting scheme showed a somewhat different pattern, with the highest potential densities allocated to freshwater wetland habitats, followed by agricultural habitats, in the Sacramento Valley (Fig. 1d). Other interior regions within the Modoc Plateau, San Joaquin Valley, and Sonoran Desert ecoregions also contained areas of relatively high habitat suitability—primarily freshwater wetlands—as did the San Francisco Bay portion of the Central Coast ecoregion.

Priority conservation areas

With conservation goals set separately for each ecoregion, Marxan-derived priority habitats varied across the state. Combining fall, winter, and spring seasons, using an "even" habitat weighting scheme and a 50% conservation goal for shorebirds, most of the frequently selected planning units (planning units selected $\geq$7 out of 10 times by Marxan, hereafter "shorebird priority areas") in coastal and inland desert ecoregions were centered on large water bodies, including San Francisco Bay and the Salton Sea (Fig. 2a). In the San Joaquin Valley, Sacramento Valley, and Modoc Plateau ecoregions, shorebird priority areas were much more widely dispersed, with more land required to support the conservation goals. Most of the priority areas were clustered around freshwater emergent wetland

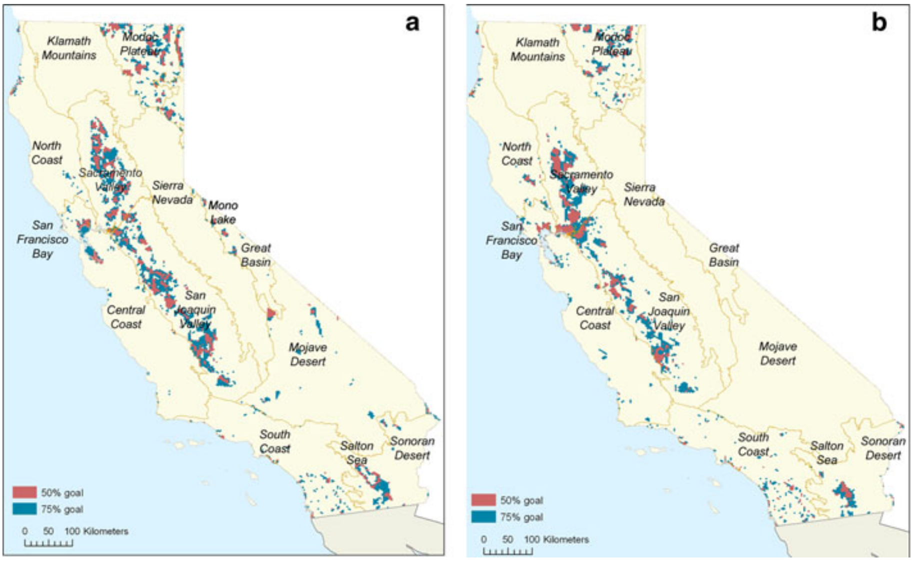

Fig. 2 California priority areas to meet 50 and 75% conservation goals for **a** fall, winter, and spring shorebirds; and **b** winter waterfowl, based on the Marxan "sum solution" (hexagonal planning units that were selected by Marxan $\geq$7 times out of 10). Results were stratified by ecoregion and Central Valley basin (shorebirds only)

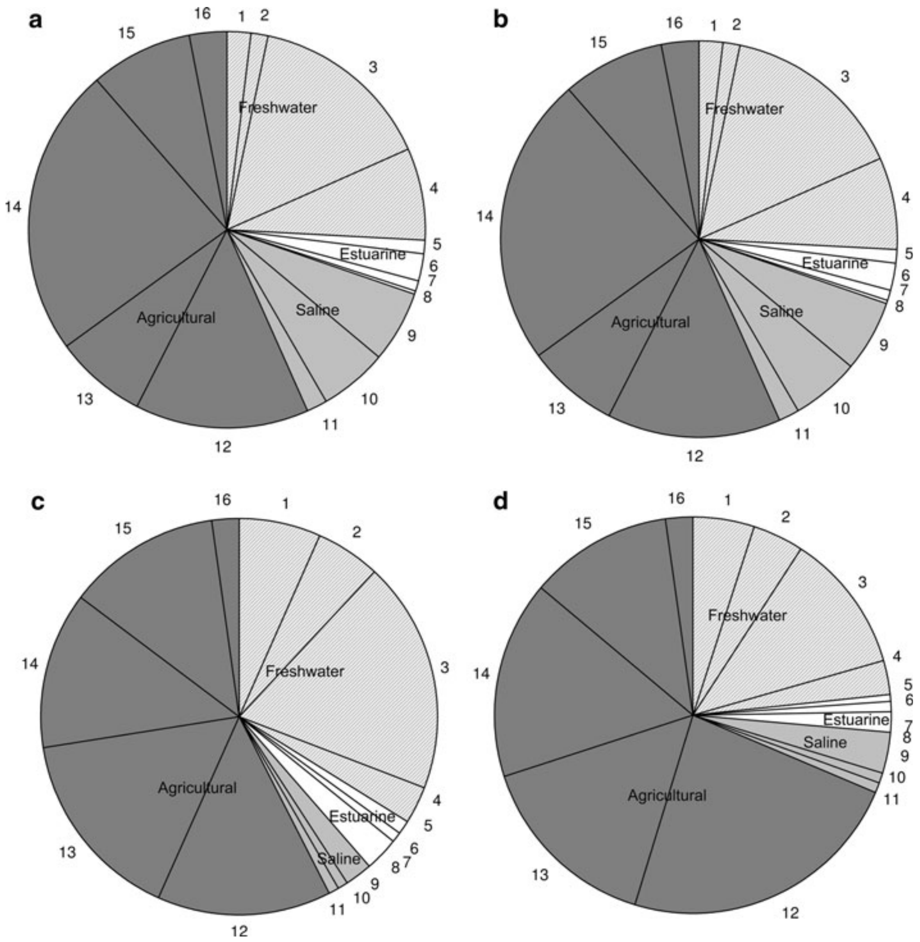

Fig. 3 Habitat types (%) selected as part of Marxan solutions (selected ≥7 times out of 10), given conservation goals of **a** 50% of fall, winter, and spring shorebird numbers, **b** 75% of fall, winter, and spring shorebird numbers, **c** 50% of winter waterfowl numbers, and **d** 75% of winter waterfowl. 1 = lake/reservoir; 2 = freshwater pond; 3 = freshwater wetland; 4 = vernal pools; 5 = tidal marsh; 6 = tidal flat; 7 = subtidal estuary; 8 = eelgrass beds; 9 = saline lake; 10 = alkali playa/lakeshore; 11 = salt pond; 12 = field crops; 13 = grain and hay crops; 14 = pasture; 15 = rice; 16 = idle cropland

habitats. All shorebird priority areas combined contained approximately 896,000 ha of waterbird habitat, 57% of which was contained in agricultural habitat types, including pasture, rice, and field crops (Fig. 3a).

With a 75% conservation goal, the total habitat area contained in all shorebird priority areas was more than twice as large (~1,974,000 ha). The spatial distribution was similar to the 50% goal (Fig. 2a), but included a greater percentage (61%) of agricultural habitats (Fig. 3b).

For the 50% waterfowl conservation goal, broad-scale regional patterns were similar to those of shorebirds, but differences in habitat suitability rankings resulted in some key differences among the Marxan-selected priority areas (Fig. 2b), and an overlap of just 24% with the shorebird priority areas for the winter season. The total area of habitat contained in

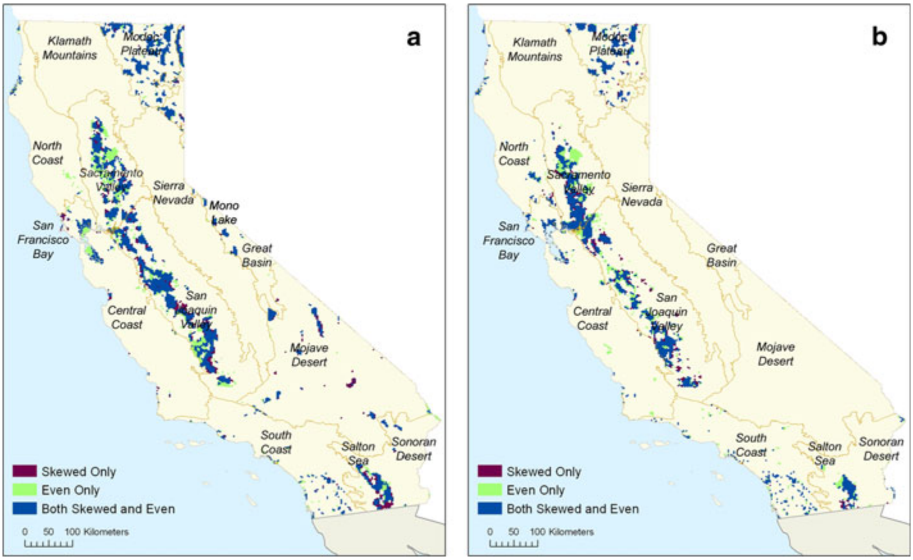

Fig. 4 Difference between "even" and "uneven" weighting schemes in Marxan solutions for **a** 75% fall, winter, and spring shorebird and **b** 75% winter waterfowl conservation goals

all priority waterfowl areas was ~661,000 ha. Similar to shorebirds, 58% of the priority habitat areas were agricultural (Fig. 3c), although they contained larger areas of grain and hay crops and smaller areas of pasture. For semi-natural habitats, waterfowl priority areas contained more freshwater wetlands, lakes, and ponds; whereas shorebird priority areas contained more saline lakes, alkali playa/lakeshore habitat, tidal flats, and vernal pools.

Using a 75% conservation goal for waterfowl, the overlap with the winter shorebird priority areas was greater, at 41%, and the total priority area (~1,433,000 ha of habitat) was more than twice as large as for the 50% goal (Fig. 2b). The distribution of habitats was weighted even more toward agricultural habitat types (67%) (Fig. 3d). Combined priority areas for wintering shorebirds and waterfowl totaled ~1,408,000 ha for the 50% goal, and ~3,114,000 ha for the 75% goal.

Using a 75% conservation goal, spatial patterns of shorebird and waterfowl priority areas resulting from an "uneven" weighting scheme were similar to, but more compact than those based on an "even" weighting scheme (Fig. 4). The area of overlap in selected planning units was 69% for shorebirds (Fig. 4a) and 68% for waterfowl (Fig. 4b). For both groups, the area of overlap between the "even" and "uneven" habitat schemes was similar to the priority habitat areas resulting from a 50% conservation goal.

Since rice may have been undervalued in the habitat rankings, we developed an alternative ranking scheme that included rice for seven additional species (Table 6 in Appendix). The resulting priority areas were quite similar to the original, overlapping by 70–72 and 85% for the 50 and 75% conservation goals, respectively (Fig. 5 in Appendix).

Conservation gaps

Our quantification of habitat ownership and conservation status indicated that, across habitat types, shorebird and waterfowl priority areas identified by Marxan were conserved at similar levels as other mapped waterbird habitats in the state (Table 3). The percent of

Table 3 Conservation status breakdown (%) by ownership and general habitat type

	Area (ha)	Federal (%)	State (%)	Other public (%)	Private, fee title (%)	Private, easement (%)	None (%)
All waterbird habitats							
Statewide	3,783,553	12	6	1	1	3	77
Shorebird solution	1,973,907	10	7	2	1	3	77
Waterfowl solution	1,433,252	7	6	1	1	3	82
Estuarine habitats							
Statewide	160,563	2	91	1	0	0	6
Shorebird solution	101,576	3	91	1	0	0	6
Waterfowl solution	44,003	5	78	1	1	0	14
Saline habitats							
Statewide	443,698	56	2	7	0	1	4
Shorebird solution	258,430	48	3	10	0	1	37
Waterfowl solution	71,695	20	8	0	0	0	71
Freshwater habitats							
Statewide	1,029,680	18	5	2	2	6	67
Shorebird solution	402,309	16	8	2	2	8	63
Waterfowl solution	328,423	20	12	2	2	7	57
Agricultural habitats							
Statewide	2,149,612	1	1	0	0	1	96
Shorebird solution	1,211,592	1	1	0	0	2	96
Waterfowl solution	967,966	2	1	0	0	2	94

Conservation status across all planning units with mapped waterbird habitats is compared with conservation status for Marxan-selected priority shorebird and waterfowl conservation areas (75% conservation goal). See Table 1 for definition of general habitat types

priority waterfowl areas conserved was actually lower than the statewide conservation percentage, primarily due to low levels of federal ownership.

With respect to general habitat categories, estuarine habitats were found to have the highest levels of conservation, with mostly state ownership, and saline habitats were also relatively well-conserved statewide. Freshwater habitats had relatively low levels of conservation (67% lacking conservation status), and agricultural lands were found to be largely un-conserved (96%) statewide.

For shorebird priority areas, estuarine and agricultural habitats were conserved at the same levels as statewide, while freshwater wetland habitats were better conserved and saline habitats were less well-conserved. For waterfowl priority areas, estuarine and saline habitats were conserved at lower levels than statewide, while freshwater and agricultural habitats had higher levels of conservation. Although conservation levels for agricultural habitats were very low in general, the percentage of land in conservation easements was twice as high for shorebird and waterfowl priority areas (2%) as statewide (1%).

Discussion

Our analysis is one of few applications of spatial habitat prioritization to regional-scale shorebird and waterfowl conservation. Using this approach, we identified a combined 3.1

million hectares of priority areas for shorebirds and waterfowl in California and revealed significant gaps in conservation status, particularly for freshwater and agricultural habitats. Our results corroborated the importance of many key priority areas for shorebirds and waterfowl in California (e.g., San Francisco Bay, Salton Sea) while also identifying efficient configurations of smaller, more dispersed habitats primarily found in agricultural landscapes.

Conservation planning approach

By incorporating bird population data and expert knowledge of habitat relationships in our estimates of habitat suitability we were able to improve upon traditional occurrence- or feature-based reserve design algorithms to take advantage of differential habitat use information across habitat types and geographic regions. Furthermore, our downscaling of regional population information into spatially explicit habitat-based conservation priorities can aid the implementation of regional population goals at the site level. We believe this hybrid approach will be valuable to the development of landscape-scale conservation and restoration strategies.

We argue that this approach combines the best elements of two conservation planning traditions: the data-rich, population-centered approach of shorebird and waterfowl conservation planning initiatives (Brown et al. 2001; Hickey et al. 2003; NAWMP 2004; CVJV 2006) and a mathematically sophisticated, efficient conservation planning algorithm from the reserve design tradition (Margules and Pressey 2000). The integration of these traditions is unique, although landbird conservation priorities were integrated in a similar exercise by Pearce et al. (2008) for the Rocky Mountain corridor.

We also integrated expert-based and systematic approaches for conservation planning, which has been acknowledged as a needed improvement to traditional approaches (Cowling et al. 2003; Meir et al. 2004). Although the potential for personal biases to influence results could not be completely eliminated, we attempted to reduce this influence by using expert knowledge to rank habitat preferences in the abstract, rather than to prioritize specific geographic areas. This was thought to provide a reliable framework for linking empirical habitat and population data. Although we found some consistent differences in general patterns of the Marxan solutions based on habitat weighting schemes (“even” vs. “uneven”), the resulting core priority areas did not differ substantially. This suggests that, for our purposes of prioritizing conservation areas for shorebirds and waterfowl, the actual weighting factors and estimated densities were less important than the identification of habitat relationships and the spatial patterns of habitat distribution.

Conservation priorities

From this hybrid approach we were able to gain additional insights about the spatial patterns of shorebird and waterfowl habitat use in California and the areas of high priority for their conservation. While discrete sites such as major estuaries were confirmed as important for conservation of coastal populations, we found that inland conservation priorities were widely dispersed across agricultural landscapes, and required much more land area, with the exception of key water bodies.

Aside from estuarine habitats, the highest density potential across all species, according to our expert-based habitat rankings, was in semi-natural habitats such as freshwater wetlands and ponds and saline playa/lakeshore habitats, many of which rely on human management. The surrounding agricultural areas not only provide additional habitat for many species but connect larger wetland landscapes. Others have shown such connectivity to be important for increasing bird foraging potential during winter and migration (Farmer and Parent 1997; Naugle et al. 2001). Furthermore, these agricultural landscapes have great potential to be managed simultaneously for crop production and wildlife values (Elphick and Oring 1998) or to be acquired for restoration and managed specifically for shorebirds and waterfowl.

Agricultural fields are well-recognized as valuable to shorebirds and waterfowl (Reid and Heitmeyer 1995; Shuford et al. 1998; Elphick 2000), but our spatially-explicit analysis provided more detail about high-value areas within large landscapes that can inform conservation implementation. Although high quality agricultural habitats are patchily-distributed in space and time (based on the timing of management practices, precipitation, and other local conditions), we could not easily discriminate among areas of the same mapped habitat type. Thus, our identification of high-value agricultural areas was based on ecoregional count data and proximity to other more discrete high-value wetland habitats, the importance of which has been demonstrated empirically for some species, particularly in dry years (Taft and Haig 2006; Elphick 2008). This broad-scale, dispersed representation of agricultural habitat value conservatively reflects mean long-term habitat value under current management practices. Under improved management, however, the value of agricultural habitats could be greatly increased, reducing the total area of agricultural lands needed to achieve the conservation goals we evaluated.

We found relatively low overlap between conservation solutions for waterfowl and shorebirds, which often occur in similar habitats with similar management. This is potentially a result of differences in survey methods. For example, geese—for which grain and hay crops were ranked highly—were well surveyed, while shorebird species using similar upland agricultural habitats (e.g., long-billed curlew, *Numenius americanus*) were likely under-represented due to the emphasis on wetlands and flooded agriculture in the shorebird surveys.

Also contributing to the low level of overlap was the BLM setting in Marxan, which assigned relatively little importance to solution compactness, thereby making solutions more sensitive to small differences in habitat rankings across the two groups. Even with a relatively large goal of 75%, however, the overlap between waterfowl and shorebirds was just 41%, suggesting some real separation in the spatial configuration of habitats that cover the diverse needs of these groups (Elphick 2008).

Conservation gaps

As demonstrated for other ephemeral wetland systems (Poor 1999; Naugle et al. 2001) our conservation gap analysis showed that agricultural habitats are much less conserved than other wetland habitats. Yet we did find relatively low levels of conservation management overall for freshwater habitats (including wetlands). Furthermore, the percentage of conserved shorebird and waterfowl habitat within our Marxan solutions was not generally higher than for California as a whole, suggesting that shorebird and waterfowl habitats are underrepresented in current conservation management. Although agricultural management practices that are beneficial to shorebirds and waterfowl can be provided without formal protection, these lands are vulnerable to loss and crop-type conversion based on factors such as population growth and urban expansion, climate change and water uncertainty, and unpredictable fluctuations in the global agricultural economy. Traditional habitat protection strategies such as conservation and agricultural easements and fee acquisitions may be of limited utility for protecting and managing significant areas of agricultural lands, however (Rilla 2002). Instead, conservation strategies focused on incentive-based programs to support wildlife friendly management practices in agricultural settings (e.g., Burger 2006)—for example, maximizing waterbird use of flooded fields by improving the timing, quality and quantity of water used—may have greater utility and conservation effectiveness (e.g., CVJV 2006).

Conservation implications

Our study suggests that more conservation effort should be focused on the largely privately owned agricultural landscapes of California, including portions of the Sacramento and San Joaquin Valleys, Modoc Plateau (Klamath Basin), and Sonoran Desert (Imperial Valley) ecoregions. The importance of agricultural habitats has been well-recognized by shorebird and waterfowl conservation initiatives (Hickey et al. 2003; Eadie et al. 2008). However, these habitats and the migratory waterbirds they support are not typically effectively incorporated in regional biodiversity conservation planning efforts. The value of these landscapes to shorebirds and waterfowl depends on the timing and distribution of available water; thus, their conservation will depend upon the identification, securing and management of water resources, in addition to traditional land acquisition and easements.

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Appendix

See Tables 4, 5, 6 and Fig. 5.

Table 4 Mean count numbers and coefficients of variation for all shorebird and waterfowl study species combined, by California ecoregion and season

Season[a]	Group[b]	Ecoregion	YRS[c]	SITES[d]	Mean[e]	CV[f]
Fall	S	California Central Coast	3	12	436,734	0.09
Fall	S	California North Coast	4	3.8	39,063	0.39
Fall	S	California South Coast	4	19.3	49,859	0.14
Fall	S	East Cascades—Modoc Plateau	6	8	16,685	0.57
Fall	S	Great Basin	6	3.8	31,419	0.43
Fall	S	Great Central Valley—Sacramento	3	31.3	46,315	0.23
Fall	S	Great Central Valley—San Joaquin	3	10.3	87,399	0.37
Fall	S	Mojave Desert	7	4.3	5,487	0.30
Fall	S	Sierra Nevada	5	1	79	0.48
Fall	S	Sonoran Desert	7	1.42	80,134	0.39
Winter	S	California Central Coast	3	11.7	435,192	0.06
Winter	S	California North Coast	4	3.3	60,555	0.29
Winter	S	California South Coast	2	15	48,663	0.001
Winter	S	Great Central Valley—Sacramento	2	30	73,613	0.31
Winter	S	Great Central Valley—San Joaquin	2	11	137,528	0.12

Table 4 continued

Season[a]	Group[b]	Ecoregion	YRS[c]	SITES[d]	Mean[e]	CV[f]
Winter	S	Mojave Desert	3	5	700	0.49
Winter	S	Sonoran Desert	4	1.3	29,278	0.45
Spring	S	California Central Coast	6	9.7	760,300	0.16
Spring	S	California North Coast	5	3.4	36,548	0.75
Spring	S	California South Coast	5	18.2	65,966	0.36
Spring	S	Columbia Plateau	1	2	5,468	–
Spring	S	East Cascades—Modoc Plateau	6	10.5	27,078	0.50
Spring	S	Great Basin	6	3.2	11,618	0.80
Spring	S	Great Central Valley—Sacramento	3	29	127,439	0.33
Spring	S	Great Central Valley—San Joaquin	3	10	201,638	0.36
Spring	S	Mojave Desert	7	4.7	12,179	0.49
Spring	S	Sierra Nevada	6	1	429	0.26
Spring	S	Sonoran Desert	7	1.3	788,934	0.33
Winter	W	California Central Coast	6	N/A	315,685	0.32
Winter	W	California North Coast	6	N/A	45,143	0.21
Winter	W	California South Coast	6	N/A	21,843	0.50
Winter	W	East Cascades—Modoc Plateau	6	N/A	186,256	0.68
Winter	W	Great Central Valley—Sacramento	6	N/A	3,214,896	0.18
Winter	W	Great Central Valley—San Joaquin	6	N/A	811,525	0.17
Winter	W	Sonoran Desert	6	N/A	62,121	0.50

Shorebird data are based on surveys conducted from 1988 to 1995 as part of PRBO's Pacific Flyway Project. Waterfowl data are based on surveys conducted from 2000 to 2005 as part of the mid-winter waterfowl counts organized by the California Department of Fish and Game and the U.S. Fish and Wildlife Service

[a] Fall = Aug–Oct, Early winter = Nov–Dec, Late winter = Jan–Feb, Spring = April

[b] S = Shorebirds, W = waterfowl

[c] Number of years included in calculations

[d] Mean number of sites

[e] Mean number of total birds

[f] Coefficient of variation of mean number of total birds

Table 5 Habitat rankings for shorebird and waterfowl study species, as designated by waterbird experts

Common name, scientific name	Ranking							
	#1	# 2	# 3	# 4	# 5	# 6	# 7	# 8
Mallard, *Anas platyrhynchos*	3	2	7	14				
Gadwall, *A. strepera*	3	16	12	13	2	7		
American wigeon, *A. americana*	3	16	12	13	2	7		
Green-winged teal, *A. crecca*	3	16	12	13	2	7		
Cinnamon teal, *A. cyanoptera*	3	16	12	13	2	7		
Northern shoveler, *A. clypeata*	11	3	2	9				
Northern pintail, *A. acuta*	3	16	12	13	2	7		
Wood duck, *Aix sponsa*	2	1						

Table 5 continued

Common name, scientific name	Ranking							
	#1	# 2	# 3	# 4	# 5	# 6	# 7	# 8
Redhead, *Aythya americana*	3	2						
Canvasback, *A. valisineria*	7	2	3					
Greater scaup, *A. marila*	7							
Lesser scaup, *A. affinis*	11	3	1	2				
Ring-necked duck, *A. collaris*	3	2						
Common goldeneye, *Bucephala clangula*	2	1	7					
Bufflehead, *B. albeola*	7	1	2	3				
Ruddy duck, *Oxyura jamaicensis*	7	1	9	11				
Snow goose, *Chen caerulescens*	13	15	3					
Ross's goose, *C. rossii*	13	15	3					
Greater white-fronted goose, *Anser albifrons*	13	15	3					
Canada goose, *Branta canadensis*	13	15	3	14				
Aleutian cackling goose, *B. hutchinsii*	13	3	14					
Brant, *B. bernicla*	8	7						
Tundra swan, *Cygnus columbianus*	13	3	1	2	15			
Sandhill crane, *Grus canadensis*	13	3	15	14				
American coot, *Fulica americana*	3	2	7					
Red-necked phalarope, *Phalaropus lobatus*	9	11	7	3				
Wilson's phalarope, *P. tricolor*	9	11	3					
American avocet, *Recurvirostra americana*	10	11	6	9	1			
Black-necked stilt, *Himantopus mexicanus*	3	11	5	10	9	2		
Short-billed dowitcher, *Limnodromus griseus*	6							
Long-billed dowitcher, *L. scolopaceus*	3	16	12	13	6			
Least sandpiper, *Calidris minutilla*	6	3	15	16	12	13	10	5
Dunlin, *C. alpina*	6	3	15	16	12	13	11	
Western sandpiper, *C. mauri*	6	3	10	11				
Marbled godwit, *Limosa fedoa*	6							
Greater yellowlegs, *Tringa melanoleuca*	3	4	2	15	5			
Willet, *T. semipalmata*	6	5	11					
Long-billed curlew, *Numenius americanus*	14	6	15	5	4			
Whimbrel, *N. phaeopus*	14	6	3	5				
Black-bellied plover, *Pluvialis squatarola*	6	14	3					
Killdeer, *Charadrius vociferus*	14	16	12	13	3	15	10	6
Semipalmated plover, *Charadrius semipalmatus*	6	3	11					

Habitat codes: 1 = lake/reservoir; 2 = freshwater pond; 3 = freshwater wetland; 4 = vernal pools; 5 = tidal marsh; 6 = tidal flat; 7 = subtidal estuary; 8 = eelgrass beds; 9 = saline lake; 10 = alkali playa/lakeshore; 11 = salt pond; 12 = field crops; 13 = grain and hay crops; 14 = pasture; 15 = rice; 16 = idle cropland

Table 6 Revised habitat rankings for shorebird and waterfowl study species, as designated by waterbird experts in response to reviewer feedback

Common name, scientific name	Ranking							
	#1	# 2	# 3	# 4	# 5	# 6	# 7	# 8
Mallard, *Anas platyrhynchos*	3	2	7	14				
Gadwall, *A. strepera*	3	15	16	12	13	2	7	
American wigeon, *A. americana*	3	15	16	12	13	2	7	
Green-winged teal, *A. crecca*	3	15	16	12	13	2	7	
Cinnamon teal, *A. cyanoptera*	3	15	16	12	13	2	7	
Northern shoveler, *A. clypeata*	11	15	3	2	9			
Northern pintail, *A. acuta*	3	15	16	12	13	2	7	
Wood duck, *Aix sponsa*	2	1						
Redhead, *Aythya americana*	3	2						
Canvasback, *A. valisineria*	7	2	3					
Greater scaup, *A. marila*	7							
Lesser scaup, *A. affinis*	11	3	1	2				
Ring-necked duck, *A. collaris*	3	2						
Common goldeneye, *Bucephala clangula*	2	1	7					
Bufflehead, *B. albeola*	7	1	2	3				
Ruddy duck, *Oxyura jamaicensis*	7	1	9	11				
Snow goose, *Chen caerulescens*	13	15	3					
Ross's goose, *C. rossii*	13	15	3					
Greater white-fronted goose, *Anser albifrons*	13	15	3					
Canada goose, *Branta canadensis*	13	15	3	14				
Aleutian cackling goose, *B. hutchinsii*	13	3	14	15				
Brant, *B. bernicla*	8	7						
Tundra swan, *Cygnus columbianus*	13	3	1	2	15			
Sandhill crane, *Grus canadensis*	13	3	15	14				
American coot, *Fulica americana*	3	2	15	7				
Red-necked phalarope, *Phalaropus lobatus*	2	13	10	5				
Wilson's phalarope, *P. tricolor*	2	13	5					
American avocet, *Recurvirostra americana*	10	11	6	9	1	15		
Black-necked stilt, *Himantopus mexicanus*	3	11	5	10	9	2		
Short-billed dowitcher, *Limnodromus griseus*	6							
Long-billed dowitcher, *L. scolopaceus*	3	16	15	12	13	6		
Least sandpiper, *Calidris minutilla*	6	3	15	16	12	13	10	5
Dunlin, *C. alpina*	6	3	15	16	12	13	11	
Western sandpiper, *C. mauri*	6	3	10	11				
Marbled godwit, *Limosa fedoa*	6							
Greater yellowlegs, *Tringa melanoleuca*	3	4	2	15	5			
Willet, *T. semipalmata*	6	5	11					
Long-billed curlew, *Numenius americanus*	14	6	15	5	4			
Whimbrel, *N. phaeopus*	14	6	3	5				
Black-bellied plover, *Pluvialis squatarola*	6	14	3					

Table 6 continued

Common name, scientific name	Ranking							
	#1	# 2	# 3	# 4	# 5	# 6	# 7	# 8
Killdeer, *Charadrius vociferus*	14	16	12	13	3	15	10	6
Semipalmated plover, *Charadrius semipalmatus*	6	3	11					

Habitat codes: 1 = lake/reservoir; 2 = freshwater pond; 3 = freshwater wetland; 4 = vernal pools; 5 = tidal marsh; 6 = tidal flat; 7 = subtidal estuary; 8 = eelgrass beds; 9 = saline lake; 10 = alkali playa/lakeshore; 11 = salt pond; 12 = field crops; 13 = grain and hay crops; 14 = pasture; 15 = rice; 16 = idle cropland

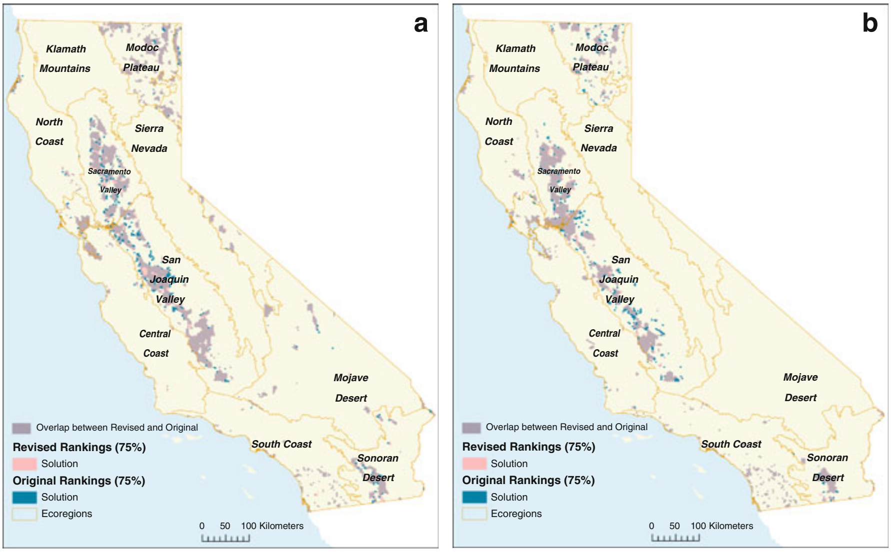

Fig. 5 Overlap between Marxan habitat priorities based on original (Table 5 in Appendix) and revised (Table 6 in Appendix) habitat rankings for **a** 75% fall, winter, and spring shorebird and **b** 75% winter waterfowl conservation goals

References

Bailey RG (1995) Description of the ecoregions of the United States, 2nd edn. Misc Pub 1391. USDA Forest Service, Washington, DC

Ball IR, Possingham HP, Watts M (2009) Marxan and relatives: software for spatial conservation prioritisation. In: Moilanen A, Wilson KA, Possingham HP (eds) Spatial conservation prioritisation: quantitative methods and computational tools. Oxford University Press, Oxford, UK

Banks RC, Springer PF (1994) A century of population trends of waterfowl in western North America. Stud Avian Biol 15:134–146

Brown S, Hickey C, Harrington B et al (2001) United States shorebird conservation plan, 2nd edn. Manomet Center for Conservation Sciences, Manomet, MA

Burger LW (2006) Creating wildlife habitat through federal farm programs: an objective-driven approach. Wildl Soc Bull 34(4):994–999

Cowling RM, Pressey RL, Sims-Castley R et al (2003) The expert or the algorithm?—comparison of priority conservation areas in the Cape Floristic Region identified by park managers and reserve selection software. Biol Conserv 112:147–167

CVJV (2006) Central Valley joint venture implementation plan—conserving bird habitat. U.S. Fish and Wildlife Service, Sacramento, CA

Dahl TE (1990) Wetlands losses in the United States 1780s to 1980s. U.S. Department of the Interior, Fish and Wildlife Service, Washington, DC, p 13

Davidson NC, Evans PR (1986) The role of man-made and man-modified wetlands in the enhancement of the survival of overwintering shorebirds. Colon Waterbirds 9:176–188

Eadie JM, Elphick CS, Reinecke KJ et al (2008) Section 1: wildlife values of North American Ricelands. In: Manley SW (ed) Conservation in ricelands of North America. The Rice Foundation, Stuttgart, AK

Eggeman DR, Johnson FA (1989) Variation in effort and methodology for the midwinter waterfowl inventory in the Atlantic Flyway. Wildl Soc Bull 17:227–233

Elphick CS (2000) Functional equivalency between rice fields and seminatural wetland habitats. Conserv Biol 14:181–191

Elphick CS (2008) Landscape effects on waterbird densities in California rice fields: taxonomic differences, scale-dependence, and conservation implications. Waterbirds 31:62–69

Elphick CS, Oring LW (1998) Winter management of Californian rice fields for waterbirds. J Appl Ecol 35:95–108

Farmer AH, Parent AH (1997) Effects of the landscape on shorebird movements at spring migration stopovers. Condor 99:698–707

Heitmeyer ME, Connelly DP, Pederson RL (1989) The Central, Imperial, and Coachella valleys of California. In: Smith LM, Pederson RL, Kiminski RM (eds) Habitat management for migrating and wintering waterfowl in North America. Texas Tech. Univ. Press, Lubbock, TX

Hickey C, Shuford WD, Page GW et al (2003) Southern Pacific shorebird conservation plan: a strategy for supporting California's central and coastal shorebird populations, vol 1.1. PRBO Conservation Science, Stinson Beach, CA

Margules CR, Pressey RL (2000) Systematic conservation planning. Nature 405:243–253

Meir E, Andelman S, Possingham HP (2004) Does conservation planning matter in a dynamic and uncertain world? Ecol Lett 7:615–622

Naugle DE, Johnson RR, Estey ME et al (2001) A landscape approach to conserving wetland bird habitat in the prairie pothole region of eastern South Dakota. Wetlands 21:1–17

NAWMP (2004) North American Waterfowl Management Plan 2004. Implementation framework: strengthening the biological foundation. Canadian Wildlife Service, U.S. Fish and Wildlife Service, Secretaria de Medio Ambiente y Recursos Naturales

Page GW, Gill RE (1994) Shorebirds in western North America: late 1800s to late 1900s. Stud Avian Biol 15:147–160

Page GW, Stenzel LE, Kjelmyr JE (1999) Overview of shorebird abundance and distribution in wetlands of the Pacific Coast of the contiguous United States. Condor 101:461–471

Pearce JL, Kirk DA, Lane CP et al (2008) Prioritizing avian conservation areas for the Yellowstone to Yukon Region of North America. Biol Conserv 141:908–924

Poor PJ (1999) The value of additional central flyway wetlands: the case of Nebraska's rainwater basin wetlands. J Agric Resour Econ 24:253–265

Possingham HP, Ball I, Andelman S (2000) Mathematical methods for reserve system design. In: Ferson S, Burgman M (eds) Quantitative methods for conservation biology. Springer, New York, NY

Pressey RL, Possingham HP, Day JR (1997) Effectiveness of alternative heuristic algorithms for identifying indicative minimum requirements for conservation reserves. Biol Cons 80:207–219

Reid FA, Heitmeyer ME (1995) Waterfowl and rice in California's Central Valley. Calif Agric 49:62

Reinecke KJ, Loesch CR (1996) Integrating research and management to conserve wildfowl (Anatidae) and wetlands in the Mississippi Alluvial Valley, USA. Gibier Faune Sauvage Game Wildl 13:927–940

Rilla E (2002) Landowners, while pleased with agricultural easements, suggest improvements. Calif Agric 56:21–25

Scott JM, Davis F, Csuti B et al (1993) Gap analysis: a geographic approach to protection of biodiversity. Wildl Monogr 123:1–41

Shuford WD, Page GW, Kjelmyr JE (1998) Patterns and dynamics of shorebird use of California's Central Valley. Condor 100:227–244

Skagen SK, Knopf FL (1993) Toward conservation of midcontinental shorebird migrations. Conserv Biol 7:533–541

Taft OW, Haig SM (2006) Landscape context mediates influence of local food abundance on wetland use by wintering shorebirds in an agricultural valley. Biol Conserv 128:298–307
Theobald D (2005) Landscape patterns of exurban growth in the USA from 1980 to 2020. Ecol Soc 10:1–32
Williams P, Gibbons D, Margules C et al (1996) A comparison of richness hotspots, rarity hotspots, and complimentary areas for conserving diversity of British birds. Conserv Biol 10:155–174