AUDUBON CALIFORNIA TECHNICAL REPORT

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Hedgerow Effects on Birds and Water Quality in California's Central Valley

February 2014

Abstract

Agricultural development in California's Central Valley has reduced habitat for native bird populations and negatively affected water quality. Anecdotal evidence suggests that planting linear strips of native vegetation, called hedgerows, between fields could simultaneously benefit birds (by providing habitat) and improve water quality (by filtering pollutants). Building on pilot surveys conducted in 2012, we designed this study to estimate the impacts of planting hedgerows on birds and water quality. Birds were surveyed during two seasons, winter 2012-2013 and spring 2013, at hedgerow and control sites, noting both the abundance and diversity of species present. Data were then analyzed using statistical models to better understand the effects of hedgerows and other landscape features on bird species richness and abundance. Moreover, model results were used to project the potential benefits of planting hedgerows across the Central Valley Ecoregion as a whole. To evaluate hedgerow effects on water quality, nitrogen removal from irrigation water was measured at both hedgerow and control sites during the summer of 2013. Our results suggest that hedgerows increase bird species richness and average abundance, and improve water quality by reducing the amount of nitrogen entering irrigation ditches. Significantly more taxa are restricted to, or more abundant at, hedgerow than control sites during the spring. Mapping these results to the Central Valley Ecoregion highlights areas where hedgerows can increase species richness by up to 36% and average abundance by over 20-fold. Moreover, there is considerable overlap between places where hedgerows have the potential to benefit birds and locations with high concentrations of nitrogen pollutants in the groundwater. This suggests significant opportunities to manage resources for humans and wildlife through the selective planting of hedgerows at locations where they are most likely to benefit birds and are most needed to mitigate nitrogen inputs and poor water quality.

Introduction

In the agricultural landscape of California's Central Valley, over 90% of the riparian, oak woodland, and shrubland habitats on the Valley floor have been lost to urban and agricultural conversion (CVJV 2006). Given that riparian and oak woodland habitats are among the most species-rich habitats in California, particularly for birds (Gaines 1977, Manley and Davidson 1993, RHJV 2004, Wilson et al. 1991, Zack et al. 2002), this has resulted in dramatic declines of many songbird species, several of which have been completely or nearly extirpated from the Valley. These changes have also degraded water quality through increased rates of sedimentation and pollutant and fertilizer runoff. Declining bird populations and water quality provide strong impetus for mitigation efforts, particularly those that address both issues simultaneously.

The transformation of weedy field margins to native hedgerows has the potential to impact California bird populations, many of which use remnant and restored riparian habitats (and other planted habitats on and around farms), to safely forage, breed, and roost. Native hedgerows, canal restorations, and other farm edge habitats have been promoted through the Natural Resources Conservation Service (NRCS) as valuable ways to increase biodiversity on farms (NRCS 2009) and enhance habitat for wildlife (Yolo County RCD 2001, Earnshaw 2004). Much of this work is based on anecdotal observation and few studies have detailed the effects on birds of hedgerow planting in California.

The small number of studies that assess the value of hedgerows as habitat for birds have come from Europe. These studies demonstrate that planted hedgerows and other on-farm habitats can contribute significantly to bird diversity and abundance in the agricultural landscape (Hinsley and Bellamy 2000, Kinross 2004) and that hedgerow structure, composition, plant diversity, and proximity to water significantly influence the value of hedgerows to birds (Hinsley and Bellamy 2000, Bonifacio et al. 2011).

A range of pollutants can be found in runoff from irrigated lands in the Central Valley of California. Pollutants include pesticides, fertilizers, salts, pathogens, and sediment. At high enough concentrations, these pollutants can negatively affect water quality and aquatic habitats. Field margins are often the first non-cultivated landscape feature that runoff interacts with, and are thus an ideal place to capture pollutants before water quality and aquatic habitats are affected. Research on vegetated field margins for water quality improvement is overwhelmingly concentrated in mesic climates in the United States, The Netherlands, the United Kingdom, and Germany (Moore et al 2005, Zhang et al 2010). This body of research suggests that field margin vegetation can reduce nitrogen export to the environment, though results vary widely depending on the details of the design implemented.

Understanding nitrogen movement provides excellent information on how biotic features such as hedgerows interact with runoff and can often serve as a proxy for other water-soluble pollutants (Herzon et al. 2008). Nitrogen is one of the most difficult pollutants to track and regulate (Rosenstock et al 2013). As a result, it is especially important to mitigate nitrogen pollution when it leaves the field. For these reasons, the literature on the effects of vegetated field margins on water quality is often focused on nitrogen pollution.

The purpose of this study was to examine the effects of native hedgerows on birds and water quality and evaluate the potential for mitigation across the entire Central Valley. Our specific objectives were to measure the effects of hedgerows on bird species richness and abundance, and the potential for hedgerow habitats to filter nitrogen. We then projected our findings throughout the Central Valley ecoregion, mapping potential benefits to birds and comparing these with the distribution of nitrogen in groundwater.

Methods

Site Selection

We selected 20 sites with hedgerows, linear field margins that have been planted with native plants, and 20 control sites, weedy field margins that have not been managed as wildlife habitat (Figure 1). The study took place in Yolo County, within the Central Valley of California (Figure 2). Both hedgerow and control sites were selected without regard to the crop type in the adjacent field; however the crop was noted and described during each survey.

Figure 1. Example of a hedgerow (left) and a weedy field margin (right).

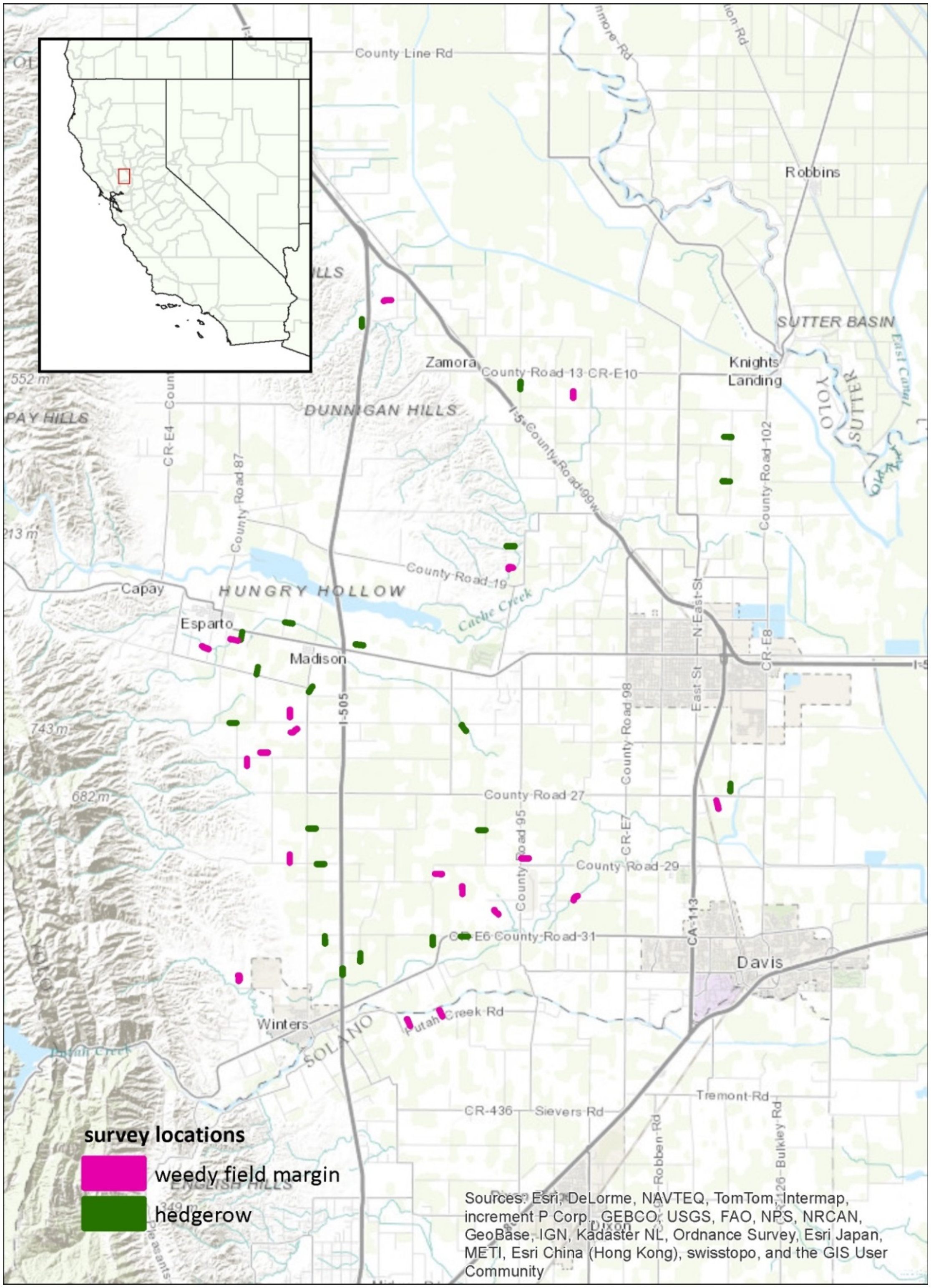

Figure 2. Locations of survey locations and description of whether they contained weedy field margins or hedgerows.

Bird Surveys

To quantify the abundance of birds using the hedgerows (or control sites), area searches were conducted every other week for the months of November, December, and January 2012-2013 and then again in April, May, and June 2013. Searches involved walking the length of the hedgerow and recording all birds seen and/or heard in the area. The search area was defined as the length of the hedgerow or farm edge (up to ~350m) including the vicinity of the hedgerow up to 3 meters on either side. Surveys began shortly after local sunrise (~0730 in winter months, ~0600 in summer months) and were completed by 1100. To standardize survey effort, the duration of each survey was proportional to the length of the transect.

Categorical Analyses

We conducted two types of categorical analyses to assess the impact of hedgerows on birds, one analysis focused on occurrence and the other focused on abundance. In the first, we compared the number of bird species that were detected exclusively at either the hedgerow or control sites. In the second, we compared the number of bird species that were more abundant at either the hedgerow or control sites. Both analyses involved the use of a Binomial test to determine if the number of bird species at the two types of sites was close to even. Separate analyses were performed for both winter and spring surveys, as we treat those two seasons independently in this study.

Modeling Bird Responses to Hedgerows within an Agricultural Landscape

We developed statistical models to describe the relationships between three response variables (i.e., species richness, average abundance, abundances of individual species) and predictor variables thought to influence the distribution and abundance of birds in the Central Valley. The predictor variables we focused on describe the agricultural context in which survey sites were situated. They included treatment (hedgerow vs. weedy field margin), adjacent field type (orchard, row crop, rice, or forage crop), distance to nearest riparian habitat, distance to nearest wooded habitat, distance to nearest urban area, and number of different habitat types within a 500 m buffer around the transect (see Table 1). The first two predictor variables were collected by observers at the time of the surveys. The last four variables were calculated using data from the National Agricultural Statistics Service (NASS) land use cropland data layer for the year 2012 (Boryan et al. 2011, Han et al. 2012, Han et al. 2014), resampled to a 100 x 100 m resolution in ArcMap 10.1.

Table 1. Description of covariates included in the analysis. The abbreviations are used to reference the covariates in the text.

Predictor	Description	Abbreviation	Data Source
Treatment	hedgerow weedy field margin	Treatment	observed
Adjacent field type	rice orchard row crop forage crop	AdjRice AdjOrchard AdjRow AdjForage	observed
Distance to nearest riparian habitat	meters from site to nearest riparian forest	RipDist	NASS
Distance to nearest wooded habitat	meters from site to nearest wooded habitat	WoodDist	NASS
Distance to nearest urban area	meters from site to nearest urban area	UrbDist	NASS
Number of different land use classes within 500 m of site	count of land use classes	Variety	NASS

We analyzed data from the winter and spring surveys separately because of the large turnover in bird species between the two periods. We used the R statistical software program for all analyses (R Development Core Team 2013). Species richness and individual species sightings were analyzed using generalized linear regression, whereas average abundance was analyzed using a generalized mixed effects model to account for variation in abundance across species.

To characterize the relationship between avian species richness and the predictor variables of interest, we summed all species recorded at a site across visits. Thus, the analysis was based on species richness by site. To characterize the relationship between average bird abundance and the predictor variables of interest, we used the total number of sightings within a site for each of the bird species encountered in the study. Thus, the analysis was based on total sightings by species by site. Species was included as a factor in the analysis to account for variation among species in overall abundance. Had we summed total sightings across species, the analysis would have heavily favored the most commonly-encountered birds. We selected two species, the Loggerhead Shrike and Song Sparrow, in order to illustrate individual species responses to the predictor variables described above. The Loggerhead Shrike analysis focused on winter patterns, while the Song Sparrow analysis was based on data from the spring season. As we did for abundance and richness, we summed all sightings for a particular species across visits within a site. Equations describing the modeled relationships are included in the Appendix.

Projections across the Central Valley Ecoregion

We generated raster layers (i.e., gridded maps) for each of the variables that entered our models so that we could make projections about how bird species richness and abundances will respond to hedgerow planting across the Central Valley Level IV Ecoregion. Two projection surfaces were created for each analysis: the first assumed the entire Central Valley is devoid of hedgerows (which is very close to the current state) and a second assuming each grid cell is planted with a hedgerow. This approach allowed us to project the magnitude of changes in bird species richness, average bird abundance, and abundance for individual bird species, if a hedgerow were planted in any given pixel. Resulting maps allow for targeted investment of conservation resources by highlighting the places that are most likely to benefit birds. All projections were generated with model-averaged parameter estimates using the “raster” package (Hijmans 2014) in R statistical software (R Core Team 2013).

Nitrogen Removal By Hedgerows

A study to evaluate nitrogen removal by hedgerows that line agricultural ditches was initiated during the 2013 summer irrigation season. Fourteen sites were selected in Yolo County, CA that exhibited a range of conditions in hedgerow plantings and hydrological features. Seven sites featured some type of hedgerow while seven did not. The effect of hedgerows on ditch-edge processes was measured by sampling soils on ditch banks for inorganic extractable nitrogen. Nitrogen removal in hedgerow soils would indicate that hedgerows are reducing the amount of nitrogen fertilizer, added to the adjacent fields, that enters ditch waters. Six soil samples–3 samples per bank–were taken at each site within a 4 day sampling period. All ditches were flowing at the time of sampling. Thirty cm depth field-moist soil cores were homogenized and extracted with 2M KCl and analyzed for two forms of nitrogen, nitrate [NO_3-N] and ammonium [NH_4-N].

Results

Categorical Analyses

A total of 75 species were detected during the winter 2012 – 2013 surveys. Of these, 18 were only detected in sites with planted hedgerows, whereas 13 were only detected in sites without hedgerows (Figure 3A, Table A1). Overall, 38 out of the 75 winter birds were more abundant at hedgerow sites, whereas 34 were more abundant at the control sites, and 3 were equally abundant across the two types of sites (Figure 3B, Table A2). These differences in presence and abundance were not statistically significant (Binomial Test, $p = 0.473$ and $p = 0.724$, respectively).

In the spring of 2013 a total of 86 birds were detected, of which 24 occurred only in hedgerows and 6 occurred only at control sites (Figure 3A, Table A1). Overall, 60 out of the 86 spring birds were more abundant at hedgerow sites, whereas only 18 were more abundant at control sites, and eight were equally abundant across the two types of sites (Figure 3B, Table A2). These differences in occurrence and abundance were both statistically significant (Binomial Test, $p = 0.001$ and $p < 0.001$, respectively).

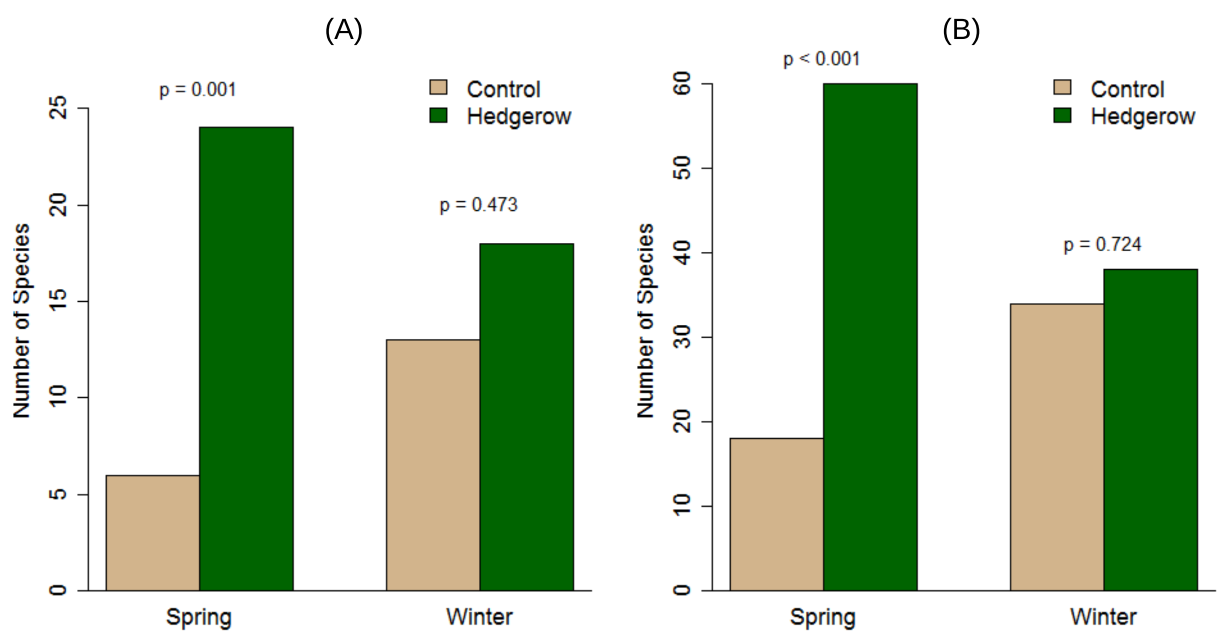

Figure 3. Number of bird species found only in hedgerow and control sites (A) and number of bird species that were more common at hedgerow and control sites (B), by season.

Species Richness

When the species richness of the winter bird community was modeled against the covariates described above, five of the covariates had positive coefficient estimates, indicating a positive effect on species richness: AdjForage, Treatment, RipDist, UrbDist, and Variety (Table 2). Three covariates had negative coefficients: AdjRice, AdjRow, and WoodDist. In the spring, six covariates had positive estimates (AdjRice, Treatment, WoodDist, RipDist, UrbDist, and Variety), and two (AdjForage and AdjRow) had negative estimates. In both seasons, the covariates with the largest positive coefficients were Treatment and UrbDist, indicating a strong positive effect of those factors on bird species richness. Conversely, AdjRow has the largest negative coefficient in both seasons, indicating a strong negative influence on species richness.

The effect of treatment—when considered in relation to all of the other covariates—was non-significant in both seasons. However, when considered alone, treatment had a significant effect on species richness in both seasons (Table S3). This shift between models is due to correlations among variables masking the significance of individual variables (e.g., treatment) in the full model.

Table 2. Modeled parameter estimates, their standard deviations, and 95% confidence intervals for species richness, by season.

Winter

Parameter	Coefficient	Std. Dev.	Lower CI	Upper CI	p < 0.05
(Intercept)	9.97	4.93	0.31	19.64	Yes
AdjacentForage	0.14	2.03	-3.85	4.13	No
AdjacentRice	-0.20	2.36	-4.82	4.41	No
AdjacentRow	-2.79	2.78	-8.23	2.65	No
RiparianDist	0.26	0.93	-1.56	2.08	No
Treatment	1.47	3.31	-5.01	7.96	No
UrbanDist	4.62	2.88	-1.02	10.27	No
Variety_500	0.15	0.31	-0.45	0.74	No
WoodDist	-0.02	0.23	-0.47	0.42	No
AdjacentForage:Treatment	-0.16	1.51	-3.12	2.81	No
AdjacentRice:Treatment	-0.04	1.36	-2.69	2.62	No
AdjacentRow:Treatment	0.14	1.33	-2.47	2.76	No
RiparianDist:Treatment	0.02	0.53	-1.03	1.07	No
UrbanDist:Treatment	0.08	1.49	-2.83	2.99	No
Variety_500:Treatment	-0.01	0.17	-0.34	0.33	No
WoodDist:Treatment	0.02	0.17	-0.31	0.34	No

Spring

Parameter	Coefficient	Std. Dev.	Lower CI	Upper CI	p < 0.05
(Intercept)	5.52	7.11	-8.41	19.46	No
AdjacentForage	-0.03	1.97	-3.89	3.82	No
AdjacentRice	0.98	3.12	-5.14	7.10	No
AdjacentRow	-1.91	2.50	-6.81	2.99	No
RiparianDist	0.37	1.04	-1.67	2.42	No
Treatment	3.62	4.43	-5.06	12.31	No
UrbanDist	3.20	3.00	-2.67	9.08	No
Variety_500	0.57	0.47	-0.35	1.49	No
WoodDist	0.15	0.34	-0.52	0.82	No
AdjacentForage:Treatment	0.07	1.36	-2.59	2.74	No
AdjacentRice:Treatment	-0.61	3.13	-6.74	5.51	No
AdjacentRow:Treatment	-0.18	1.51	-3.13	2.77	No
RiparianDist:Treatment	0.03	0.63	-1.21	1.27	No
UrbanDist:Treatment	-0.28	1.81	-3.84	3.27	No
Variety_500:Treatment	0.01	0.28	-0.53	0.55	No
WoodDist:Treatment	0.00	0.17	-0.34	0.33	No

Average Abundance

When site-level average winter abundance was modeled against the covariates described above, seven of them had positive coefficient estimates, indicating a positive effect on abundance: AdjForage, AdjRice, Treatment, WoodDist, RipDist, UrbDist, and Variety (Table 3). AdjRow was the only covariate with a negative estimate. All of these estimates, except for AdjForage, were statistically significant at an alpha level of 0.05. Two of the interaction terms had positive and five had negative coefficients. The AdjForage, AdjRice, AdjRow, and UrbDist by Treatment coefficients were statistically significant. In the spring, all of the covariates had positive coefficients and all but UrbDist were statistically significant (Table 3). All of the interaction terms except for UrbDist by Treatment were negative, and five of them (AdjRice, AdjRow, RipDist, WoodDist, and Variety) were statistically significant.

Treatment had the largest positive coefficient in spring and the second-largest in the winter, indicating positive effects on average bird abundance in both seasons. Likewise, AdjRice had the third largest effect during the winter, and the second largest effect in the spring. UrbanDist had the largest positive effect in the winter, but a very small effect in the spring. The only factor with a negative effect on average abundance during either season was AdjRow during the winter. However, several interaction terms had large negative effects in one or both seasons, including AdjRice:Treatment and AdjForage:Treatment.

Table 3. Modeled parameter estimates, their standard deviations, and 95% confidence intervals for average abundance, by season.

Season	Parameter	Coefficient	Std. Dev.	Lower CI	Upper CI	$p < 0.05$
Winter	(Intercept)	-3.21	0.31	-3.83	-2.59	Yes
	AdjacentForage	0.17	0.13	-0.09	0.43	No
	AdjacentRice	0.48	0.10	0.28	0.67	Yes
	AdjacentRow	-1.19	0.06	-1.32	-1.07	Yes
	RiparianDist	0.24	0.05	0.14	0.34	Yes
	Treatment	0.84	0.24	0.36	1.31	Yes
	UrbanDist	1.07	0.09	0.89	1.25	Yes
	Variety_500	0.10	0.01	0.07	0.12	Yes
	WoodDist	0.05	0.01	0.02	0.07	Yes
	AdjacentForage:Treatment	-0.98	0.15	-1.27	-0.69	Yes
	AdjacentRice:Treatment	-1.00	0.14	-1.26	-0.73	Yes
	AdjacentRow:Treatment	0.66	0.08	0.50	0.82	Yes
	RiparianDist:Treatment	-0.08	0.06	-0.20	0.03	No
	UrbanDist:Treatment	-0.57	0.10	-0.77	-0.37	Yes
	Variety_500:Treatment	-0.01	0.01	-0.03	0.02	No
	WoodDist:Treatment	0.01	0.01	-0.02	0.04	No

Season	Parameter	Coefficient	Std. Dev.	Lower CI	Upper CI	$p < 0.05$
Spring	(Intercept)	-5.49	0.40	-6.27	-4.71	Yes
	AdjacentForage	0.54	0.21	0.13	0.95	Yes
	AdjacentRice	2.39	0.15	2.09	2.69	Yes
	AdjacentRow	0.28	0.09	0.10	0.46	Yes
	RiparianDist	0.43	0.05	0.33	0.53	Yes
	Treatment	3.54	0.38	2.79	4.30	Yes
	UrbanDist	0.03	0.09	-0.14	0.20	No
	Variety_500	0.21	0.02	0.18	0.24	Yes
	WoodDist	0.15	0.02	0.12	0.19	Yes
	AdjacentForage:Treatment	-0.39	0.24	-0.85	0.07	No
	AdjacentRice:Treatment	-2.84	0.22	-3.27	-2.42	Yes
	AdjacentRow:Treatment	-0.42	0.12	-0.66	-0.18	Yes
	RiparianDist:Treatment	-0.37	0.06	-0.49	-0.25	Yes
	UrbanDist:Treatment	0.06	0.10	-0.14	0.26	No
	Variety_500:Treatment	-0.17	0.02	-0.20	-0.13	Yes
	WoodDist:Treatment	-0.17	0.02	-0.21	-0.13	Yes

Focal Species Abundances

Five covariates had a positive effect on Loggerhead Shrike abundance during the winter season: AdjForage, AdjRice, AdjRow, RipDist, and Treatment (Table 4). The other three, UrbDist, WoodDist, and Variety, had a slight negative effect. However, none of the covariates or interaction terms was statistically significant. For Song Sparrow abundance in the spring season, three covariates had a positive effect (AdjRice, AdjRow, and Treatment) and five had a negative effect (AdjForage, RipDist, UrbDist, WoodDist, and Variety - Table 4). The coefficients for the last three—UrbDist, WoodDist, and Variety—were statistically significant, while the others (including the interaction terms) were not.

Treatment, AdjForage, and AdjRow had large positive effects on Loggerhead Shrike abundance during the winter, whereas none of the factors had a negative effect. For Song Sparrows, Treatment, AdjRice, and AdjRow had large positive effects, but several other factors, including AdjForage and UrbDist had large negative effects on abundance.

Table 4. Modeled parameter estimates, their standard deviations, and 95% confidence intervals for the loggerhead shrike in the winter season and the song sparrow in the spring season.

	Parameter	Coefficient	Std. Dev.	Lower CI	Upper CI	p < 0.05
Loggerhead Shrike	(Intercept)	-0.50	1.21	-2.87	1.88	No
	AdjacentForage	0.49	0.70	-0.88	1.87	No
	AdjacentRice	0.12	0.52	-0.91	1.14	No
	AdjacentRow	0.33	0.57	-0.78	1.44	No
	RiparianDist	0.02	0.30	-0.57	0.61	No
	Treatment	1.31	0.92	-0.49	3.11	No
	UrbanDist	-0.02	0.33	-0.67	0.62	No
	Variety_500	-0.04	0.07	-0.18	0.09	No
	WoodDist	-0.02	0.07	-0.16	0.12	No
	AdjacentForage:Treatment	-0.05	0.37	-0.77	0.67	No
	AdjacentRice:Treatment	0.01	0.32	-0.62	0.64	No
	AdjacentRow:Treatment	0.11	0.41	-0.70	0.92	No
	RiparianDist:Treatment	-0.12	0.35	-0.80	0.56	No
	UrbanDist:Treatment	0.06	0.34	-0.61	0.73	No
	Variety_500:Treatment	0.00	0.05	-0.10	0.09	No
	WoodDist:Treatment	0.01	0.06	-0.11	0.13	No

	Parameter	Coefficient	Std. Dev.	Lower CI	Upper CI	p < 0.05
Song Sparrow	(Intercept)	-3.77	911.35	-1790.01	1782.47	No
	AdjacentForage	-7.42	966.78	-1902.31	1887.47	No
	AdjacentRice	9.49	911.35	-1776.75	1795.73	No
	AdjacentRow	9.22	911.34	-1777.02	1795.45	No
	RiparianDist	-0.11	0.36	-0.82	0.60	No
	Treatment	7.29	911.35	-1778.94	1793.53	No
	UrbanDist	-2.90	1.28	-5.42	-0.39	Yes
	Variety_500	-0.21	0.09	-0.38	-0.03	Yes
	WoodDist	-0.23	0.11	-0.46	-0.01	Yes
	AdjacentForage:Treatment	7.60	966.78	-1887.29	1902.49	No
	AdjacentRice:Treatment	-8.27	911.35	-1794.51	1777.96	No
	AdjacentRow:Treatment	-8.77	911.35	-1795.01	1777.46	No
	RiparianDist:Treatment	0.14	0.42	-0.69	0.96	No
	UrbanDist:Treatment	2.22	1.40	-0.52	4.96	No
	Variety_500:Treatment	0.01	0.07	-0.12	0.14	No
	WoodDist:Treatment	0.03	0.10	-0.17	0.24	No

Projections across the Central Valley Ecoregion

Changes in estimated total bird species richness, average bird abundance, and abundance of individual bird species as a result of adding hedgerows across the Central Valley were evident for both winter and spring seasons (Maps 1-6). The change in estimated total bird species richness increased in some areas up to 19% in the winter season and 36% in the spring season (Maps 1 & 3). Changes in estimated species richness were more pronounced during the spring season with most areas showing some amount of increase and only a few areas with no change. Changes in total average bird abundance showed both increases and decreases across the Central Valley, again with the most dramatic changes occurring during the spring season (Maps 2 & 4). Loggerhead Shrikes are expected to experience a relatively uniform increase in abundance across most of the Central Valley during the winter (Map 5). Conversely, Song Sparrows show a variable response in the spring (Map 6). There are some areas that would experience sharp increases, some that would change little, and a few spots where abundance would decline as a result of hedgerows. The patchiness of this pattern is a result of covariates interacting with treatment to influence the effect of hedgerows on Song Sparrow populations.

Nitrogen Removal by Hedgerows and Vegetated Ditches

Riparian soil nitrate was significantly lower on hedgerow ditches ($p=0.0247$, Figure 4). Low soil nitrate is indirect evidence of nitrogen removal, since denitrification removes NO_3. Plant uptake may also cause lower soil nitrate, but plant uptake should also result in lower soil ammonium. No significant differences in soil ammonium were observed, and hedgerow sites trended towards a lower ratio of soil ammonium: nitrate ($p=0.0726$), indicating that nitrate is being disproportionately removed. This suggests that denitrification, more than plant uptake, is removing soil NO_3 in hedgerow soils.

Nitrate levels in basin-fill aquifers vary considerable across the Central Valley, being highest on the western sides of the San Joaquin River from Fresno south to Bakersfield, and on the eastern side of the San Joaquin River from Stockton to Merced (Map 7). Although nitrate levels generally seem higher in the San Joaquin watershed, there are hotspots across the region, suggesting wide geographic scope for remediation efforts targeting surface sources of pollution.

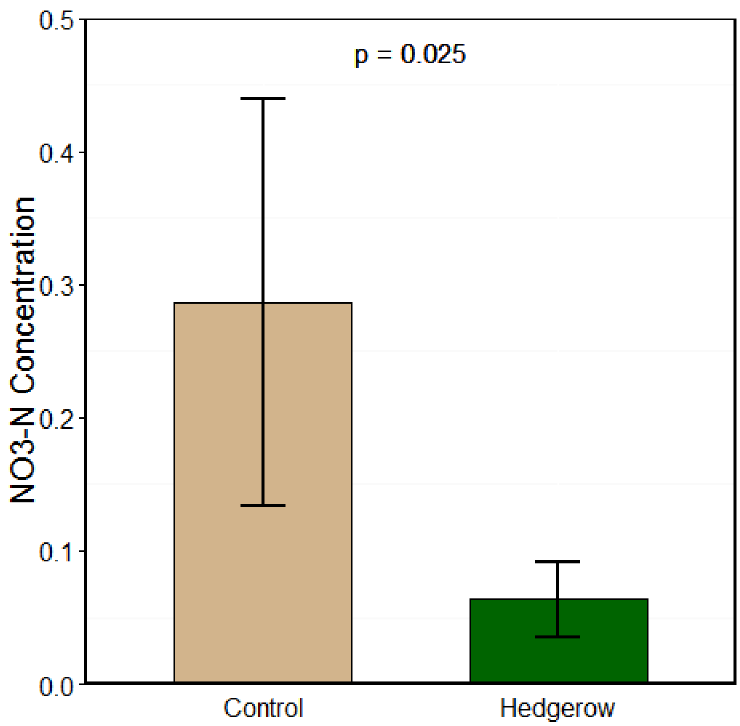

Figure 4. Soil nitrate (NO_3) concentrations at control and hedgerow sites. Bar height is the mean value across sites, the error bars represent 95% confidence intervals.

Discussion

The results of the present study provide strong evidence supporting the planting of hedgerows along field margins as a management tool to benefit wildlife and improve water quality. With respect to birds, we demonstrated that hedgerows increase species richness and average abundance relative to weedy field margins. The responses of individual species to hedgerows were mixed, but most of the birds considered were more abundant at hedgerow sites, particularly in the summer (Appendix Tables A1 & A2). With respect to water quality, hedgerows helped remove nitrogen from water that passed laterally through the hedgerow on its way to a drainage ditch. Extrapolating these results out to the Central Valley as a whole suggests significant opportunities to benefit birds while concomitantly improving water quality.

The type of crop planted in the field adjacent to the hedgerow influenced the effects of the hedgerow on birds. For example, the presence of row crops adjacent to the sample site tended to reduce bird richness—relative to hedgerows that were adjacent to orchards—in both seasons. Rice and forage crops, on the other hand, reduced richness in one season, but increased it in another. However, these effects were not statistically significant. Average bird abundance increased significantly at sampling sites adjacent to rice crops in both seasons; there was also an increase due to forage crops, but it was only significant in the spring. Row crops had contrasting effects on average bird abundance, significantly increasing it in the spring and significantly decreasing it in the winter.

Likewise, the landscape context in which the hedgerows were situated altered their effects on birds. Distance to urban and riparian areas, and the variety of habitats surrounding a site increased bird richness in both seasons, whereas distance to woody habitats increased richness in the spring, but decreased it in the winter. However, these effects were not statistically significant. Bird abundance, on the other hand, increased significantly in response to increasing distance to riparian and woody habitats, and variety in both seasons. Increasing distance to urban areas increased bird abundance in both seasons, but the effect was only significant in the winter.

The effect of hedgerows—when all other variables were held constant—was beneficial for species richness and average bird abundance in both seasons. However, when mapped to the Central Valley Ecoregion, some areas appeared to decline in species abundance in response to hedgerow planting. This effect is a result of the interaction between other landscape factors and hedgerows, particularly AdjForage and UrbDist. A likely explanation for this pattern is the fact that certain crop types and urban habitats favor a small number of abundant, generalist species to the exclusion of other birds. As such, average abundance at hedgerow sites (based just on those species that are present) is higher near urban and certain agricultural habitats than it is at hedgerow sites populated by more sensitive taxa (which tend to be less-common at the sites where they are detected).

The influence of hedgerows on birds was also modulated by season, with treatment effects being greater in the spring than the winter for both richness and abundance. This may be due to differences in bird behavior across the two seasons (i.e., breeding birds in the spring have a territory and specific needs for nesting and raising young; in winter they have fewer requirements). Alternately, this effect could be due to differences in climate between the seasons, with hotter, drier conditions making hedgerows relatively more favorable to most bird species in the spring. Regardless, the effect of season should not be misconstrued to mean that hedgerows only matter during certain times of year. As noted above, hedgerows significantly increased average bird abundance during the winter season.

The water quality results, although preliminary and lacking a seasonal component, suggest that hedgerows can reduce the amount of nitrogen—and probably other contaminants—reaching canals. Vegetation can, for example, increase the carbon content of soils to promote denitrification. Increased evapotranspiration by hedgerow vegetation can also draw ditch water into ditch-edge soils, which could promote denitrification by increasing anaerobic conditions.

Features of hedgerows such as width, age, and plant species composition likely influence their ability to filter nitrogen. These factors probably affect birds as well, and require further study.

Given that this study is based on a single year's-worth of data collected at a limited number of sites, additional research will help us to generalize the results. More specifically, additional data should be collected over time and also across more sites. Some of the non-significant results may turn out to be statistically significant once enough samples are collected to extract signal from noise. Likewise, additional sites would help to reduce the confounding effects noted in the results due to correlations between covariates. The limited geographic scope of this study also means that patterns we detected may not apply to other parts of the Central Valley. Only by collecting bird and water quality information across a wider swath of the landscape can the generality of these results be examined. A final caveat involves the water quality map depicted in Map 7. It represents nitrate concentrations in the water table, ~200 feet below the ground. We make the simplifying assumption that nitrate levels in the water table reflect nitrate levels at the surface. Better data on surface water quality in the Central Valley will allow for more effective targeting of sites for hedgerow planting.

Although further research will improve our understanding of how hedgerows benefit birds and water quality, the present results offer enough evidence to merit the attention of managers. Either of the effects reported herein—increasing bird richness and abundance, and improving water quality—would alone be reason to plant hedgerows in the Central Valley. Combined, they provide a compelling justification for management action. Moreover, the siting of future hedgerows can be guided by the maps presented in this report: they allow for the identification of sites where hedgerow planting would most benefit both birds and water quality.

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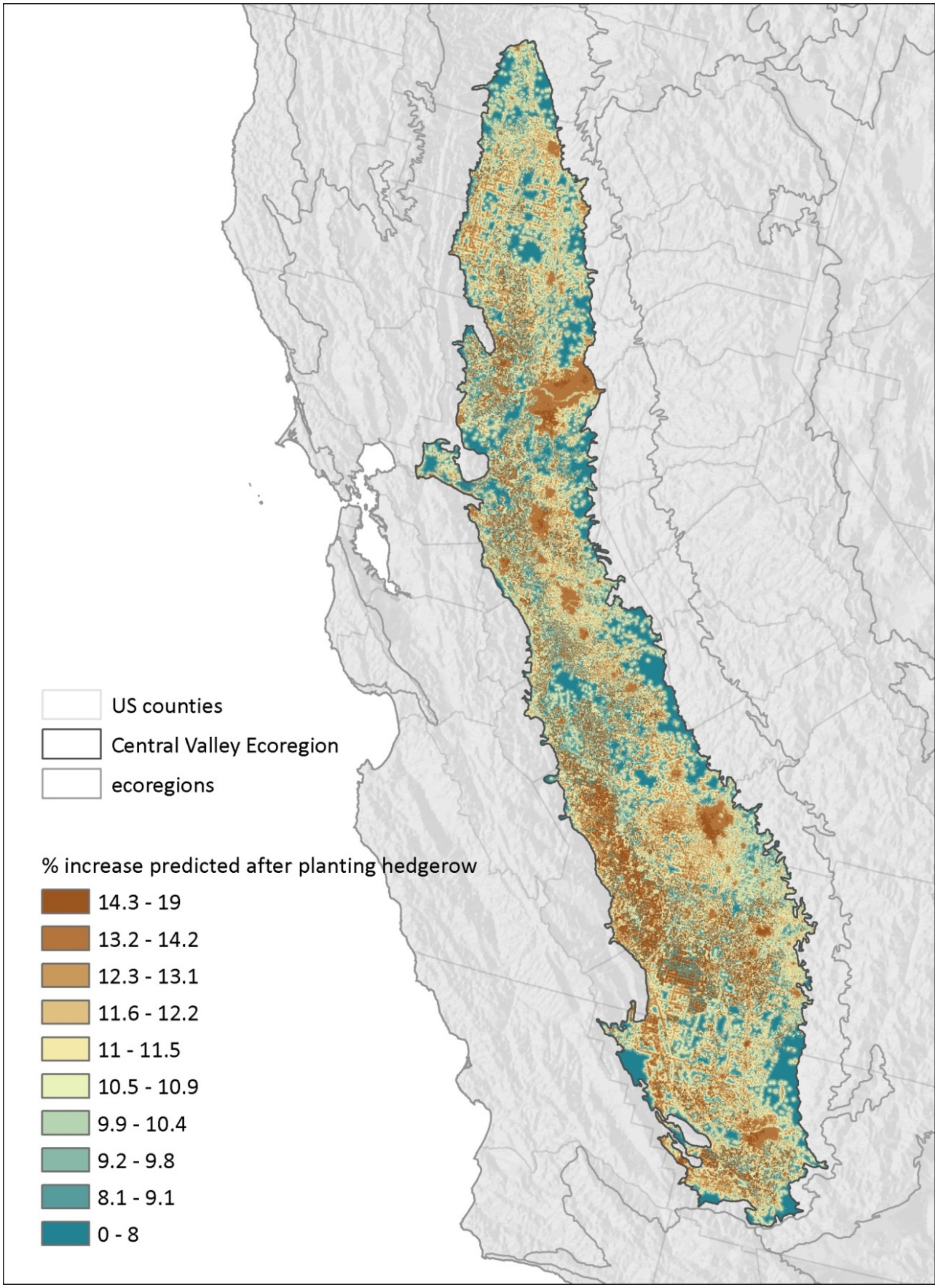
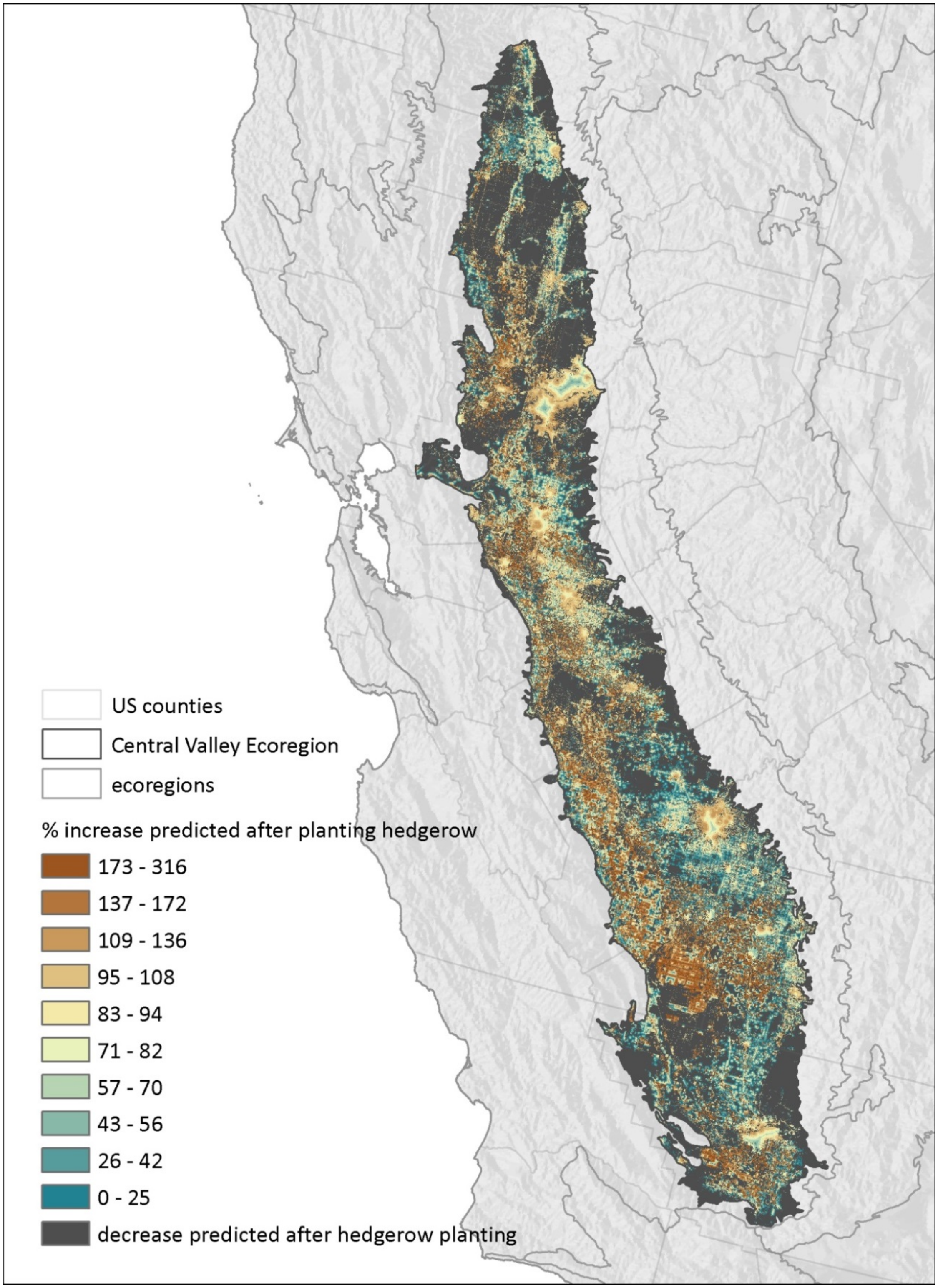
Predicted Effects of Hedgerows on Winter Bird Species Richness



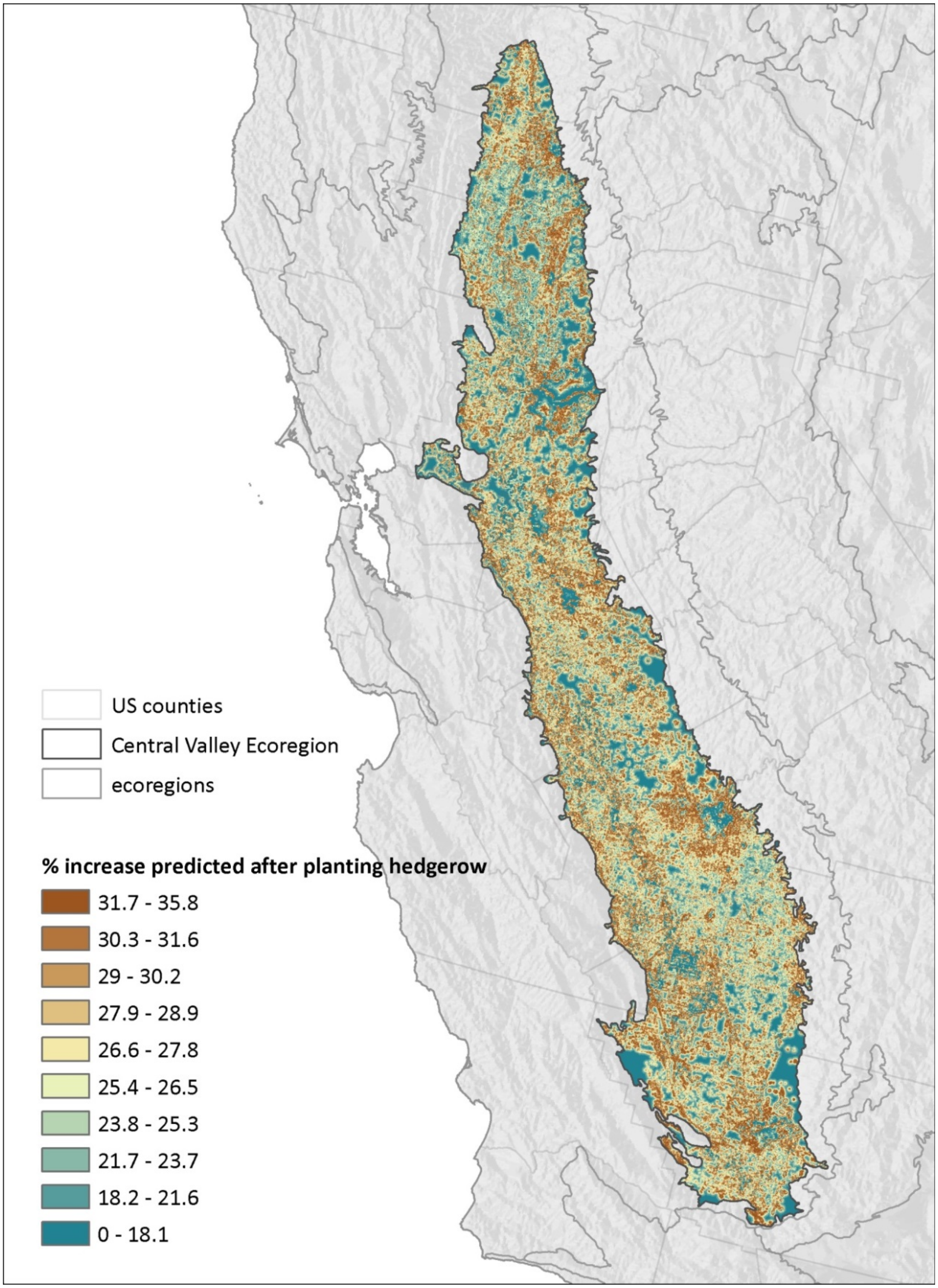
Map 1. Predicted change in the number of species occurring at a site if a hedgerow were to be planted.

Predicted Effects of Hedgerows on Winter Bird Abundance



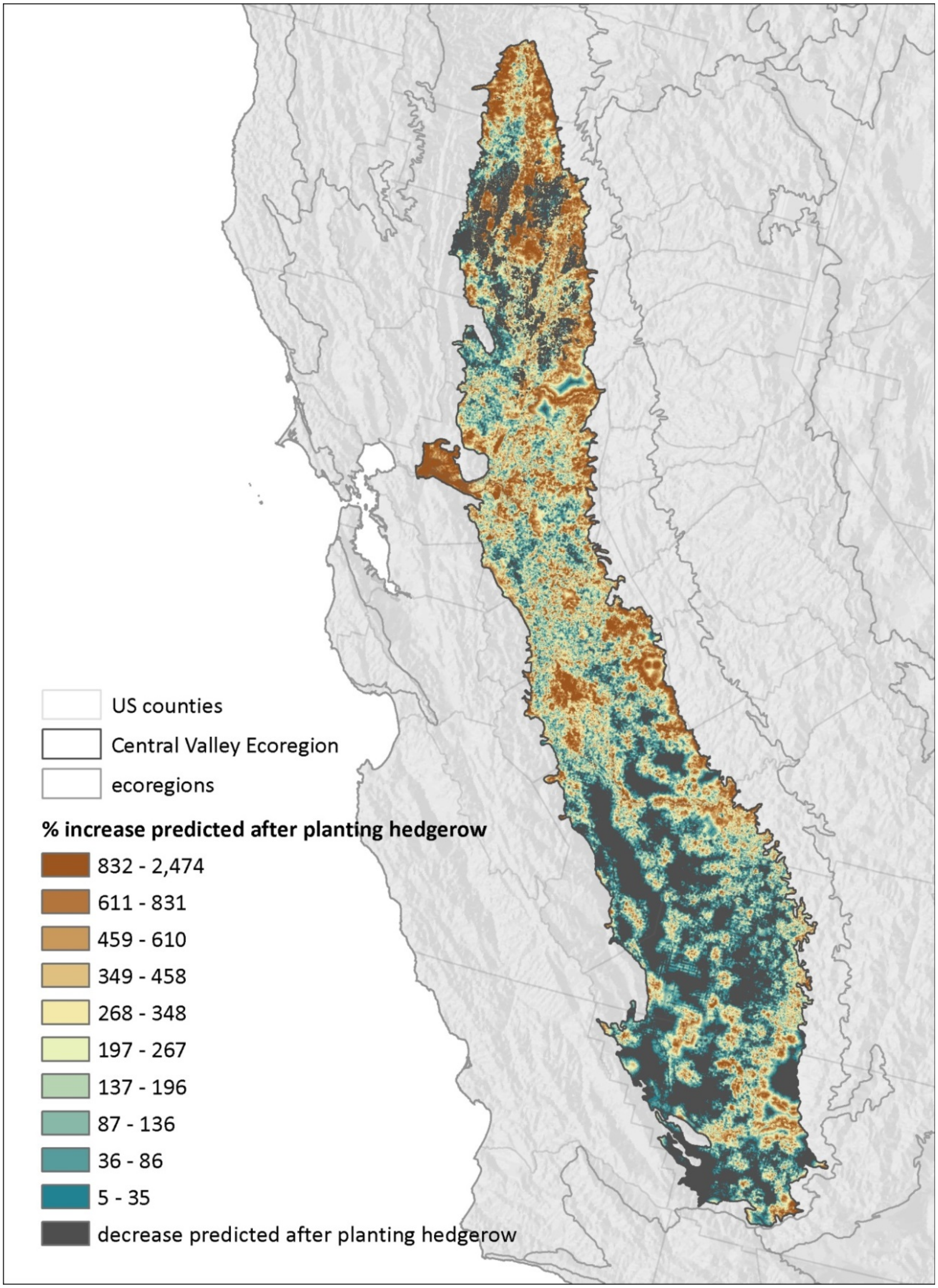
Map 2. Predicted change in the average abundance per species at a site if a hedgerow were to be planted.

Predicted Effects of Hedgerows on Spring Bird Species Richness



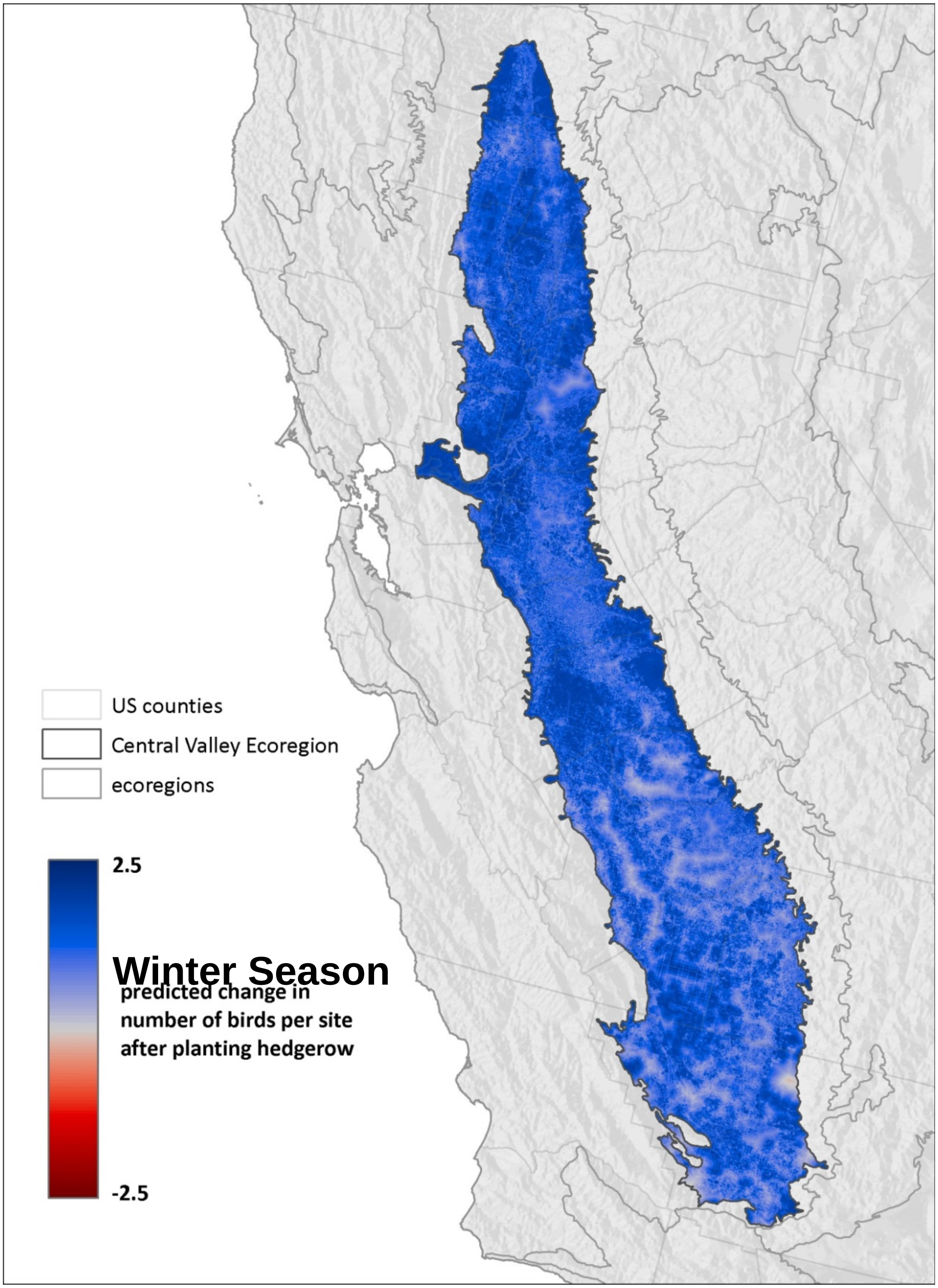
Map 3. Predicted change in the number of species occurring at a site if a hedgerow were to be planted.

Predicted Effects of Hedgerows on Spring Bird Abundance



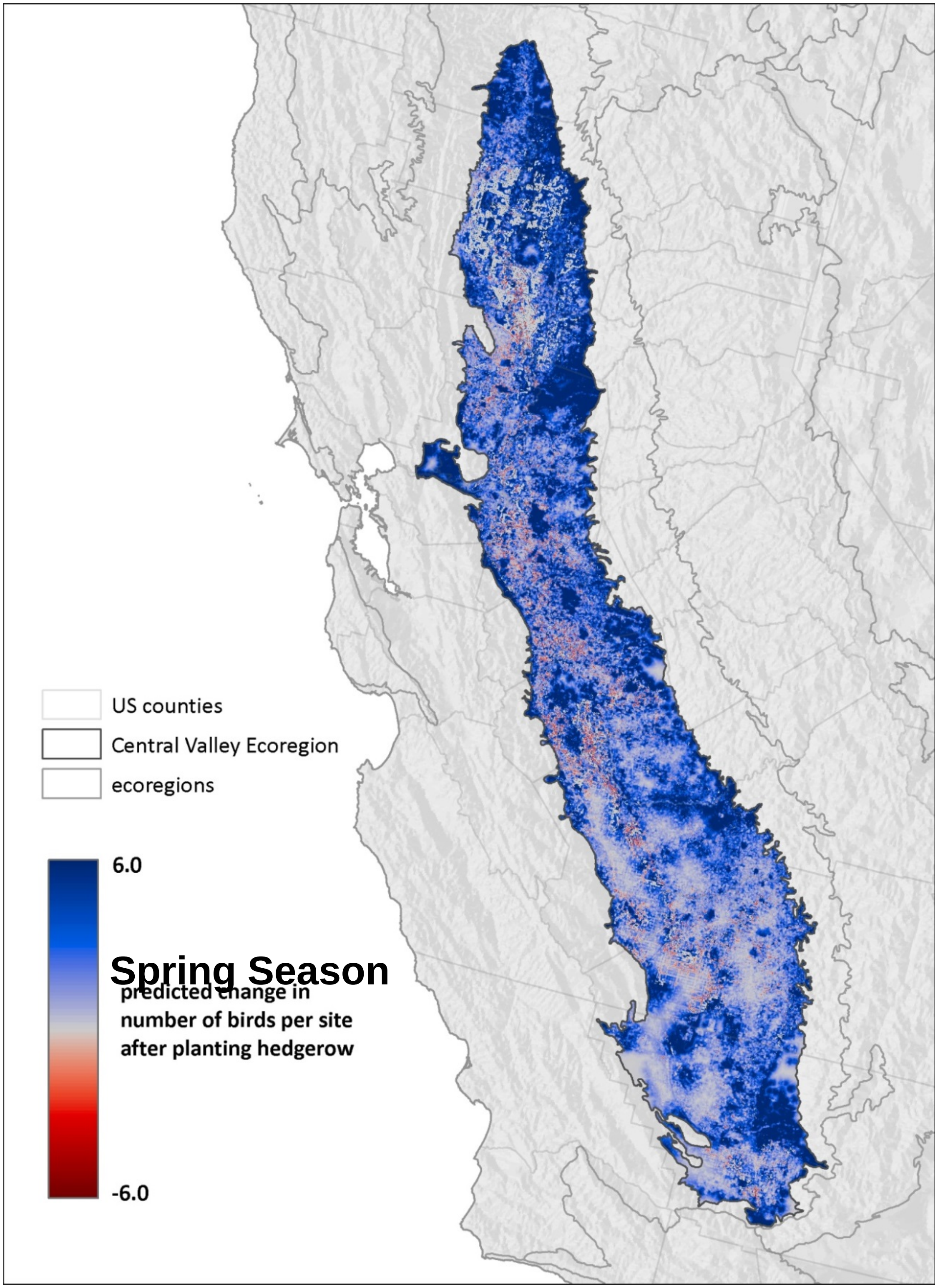
Map 4. Predicted change in the average abundance per species at a site if a hedgerow were to be planted.

Predicted Effects of Hedgerows on Loggerhead Shrike Abundance



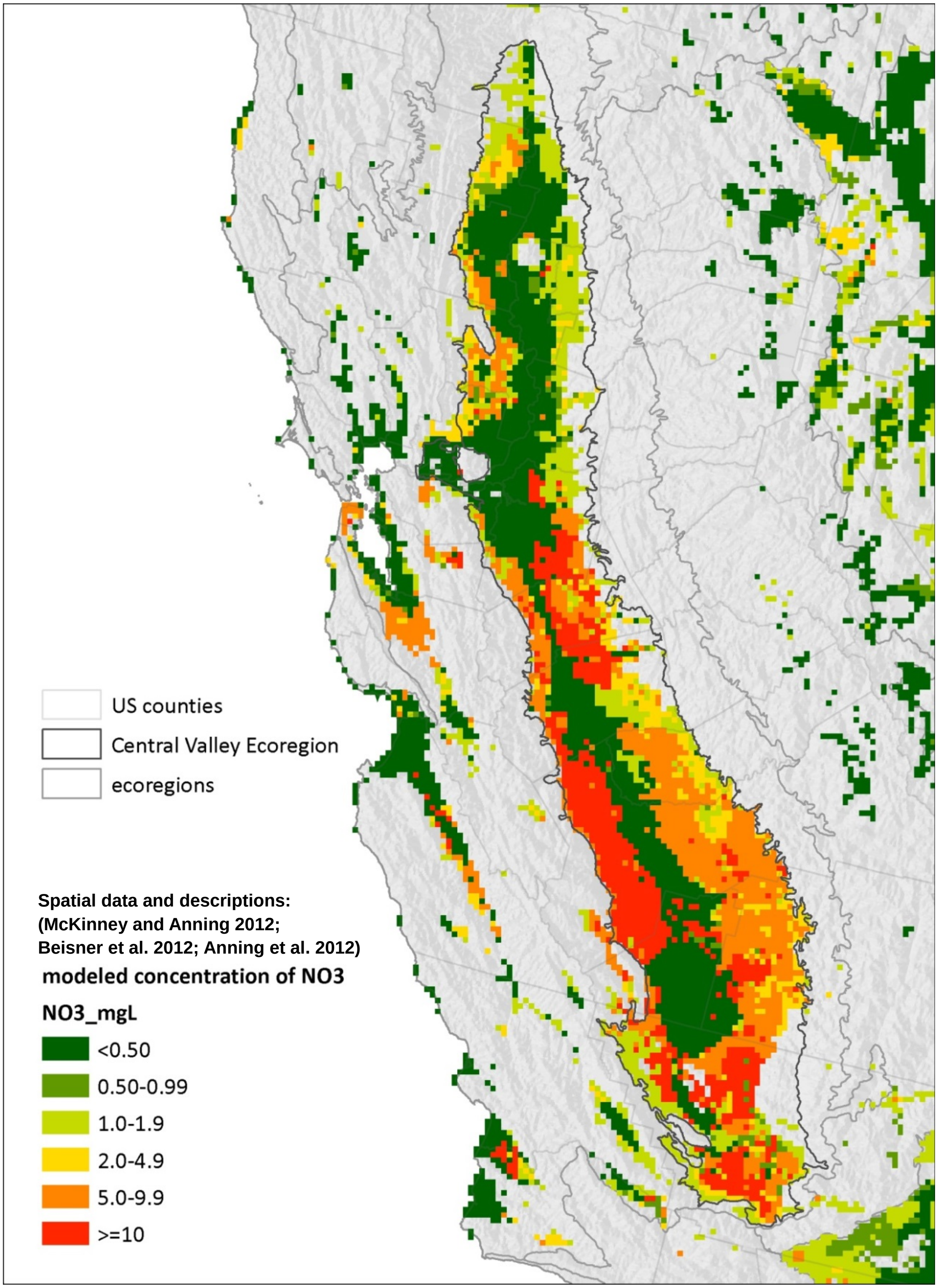
Map 5. Predicted change in the winter abundance of Loggerhead Shrikes (*Lanius ludovicianus*) at a site if a hedgerow were to be planted.

Predicted Effects of Hedgerows on Song Sparrow Abundance



Map 6. Predicted change in the spring abundance of Song Sparrows (*Melospiza melodia*) at a site if a hedgerow were to be planted.

Modeled Concentrations of Nitrate (NO_3) in Basin-Fill Aquifers



Map 7. Modeled concentration of nitrate in basin-fill aquifers throughout the Southwest. The maximum concentration limit for drinking water is 10 milligrams per liter as N.

Appendix

Model Equations

The equation to describe the relationship between avian species richness and the predictor variables of interest is as follows (see Table 1 for an explanation of abbreviations):

Treat + AdjForage + AdjRice + AdjRow + RipDist + UrbDist +

*Species Richness ~ WoodDist +Variey + Treat*AdjForage + Treat* AdjRice + Treat*AdjRow*

*+ Treat*RipDist +Treat*UrbDist + Treat*WoodDist + Treat*Variety*

Since the data had already been summed across species there was no need for a random effect term. Note that we included interaction terms between treatment and all of the other covariates to account for the effect of the covariates on the relationship between treatment and bird sightings.

The following equation describes the relationship between average bird abundance and the predictor variables of interest:

Treat + AdjForage + AdjRice + AdjRow + RipDist + UrbDist + WoodDist +

*Abundance ~ Variety + Treat*AdjForage + Treat* AdjRice + Treat*AdjRow + Treat*RipDist +*

*Treat*UrbDist + Treat*WoodDist + Treat*Variety + (Species)*

where *Species* is treated as a random effect to account for replication of data across species (and because the focus of this particular analysis was not on individual species abundances). As above, we included interaction terms between treatment and the other covariates.

The following equation describes the relationship between sightings of a particular species (Loggerhead Shrike or Song Sparrow) and the predictor variables of interest:

$$\begin{gathered} Treat + AdjForage + AdjRice + AdjRow + RipDist + UrbDist + WoodDist + \\ Sightings \sim Var500 + Treat*AdjForage + Treat*AdjRice + Treat*AdjRow + Treat*RipDist + \\ Treat*UrbDist + Treat*WoodDist + Treat*Var500 \end{gathered}$$

There was no need for a random effect term because only one species was considered at a time in this particular analysis. As above, we included interaction terms between treatment and the other covariates.

Tables

Table A1. List of species that were only detected in hedgerow or control sites, by season.

Winter Surveys		Spring Surveys	
Hedgerows	**Controls**	**Hedgerows**	**Controls**
American Goldfinch	Belted Kingfisher	Acorn Woodpecker	American Coot
Anna's Humminbird	Brown-headed Cowbird	Black-chinned Hummingbird	Northern Rough-winged Swallow
California Towhee	Brewer's Blackbird	Bewick's Wren	Purple Finch
California Quail	Bullock's Oriole	Black-headed Grosbeak	Snowy Egret
Common Raven	Burrowing Owl	Cedar Waxwing	Swainson's Thrush
Downy Woodpecker	Cedar Waxwing	Chipping Sparrow	Violet-green Swallow
Fox Sparrow	Green Heron	Downy Woodpecker	
Great-horned Owl	Hermit Thrush	Golden-crowned Sparrow	
Golden Eagle	Lark Sparrow	Grasshopper Sparrow	
Greater Roadrunner	Rough-legged Hawk	Lark Sparrow	
Marsh Wren	Rock Wren	Lazuli Bunting	
Oak Titmouse	Swainson's Hawk	Nashville Warbler	
Red-breasted Sapsucker	Western Kingbird	Northern Bobwhite	
Ring-necked Pheasant		Northern Flicker	
Sage Thrasher		Orange-crowned Warbler	
Spotted Towhee		Red-tailed Hawk	
Tree Swallow		Rufous Hummingbird	
White-breasted Nuthatch		Spotted Towhee	
		Sharp-shinned Hawk	
		Turkey Vulture	
		Western Bluebird	
		Western Wood-Pewee	
		Wild Turkey	
		White-tailed Kite	

Table A2. List of species that were more abundant in hedgerow or control sites, by season. This list includes those species listed in Table A1 (species only detected in hedgerow or control sites).

Winter Surveys		Spring Surveys	
Hedgerows	**Controls**	**Hedgerows**	**Controls**
American Crow	American Kestrel	Acorn Woodpecker	American Coot
American Goldfinch	American Robin	American Goldfinch	American Crow
American Pipit	Belted Kingfisher	American Kestrel	Barn Swallow
Anna's Hummingbird	Brown-headed Cowbird	American Robin	Black Phoebe
Bewick's Wren	Black Phoebe	Anna's Hummingbird	Brewer's Blackbird
Bushtit	Brewer's Blackbird	Ash-throated Flycatcher	Bullock's Oriole
California Towhee	Bullock's Oriole	Black-chinned Hummingbird	Cliff Swallow
California Quail	Burrowing Owl	Bewick's Wren	Eurasian Collared-Dove
Common Raven	Cedar Waxwing	Brown-headed Cowbird	European Starling
Downy Woodpecker	Dark-eyed Junco	Black-headed Grosbeak	Great Egret
European Starling	Eurasian Collared Dove	Blue Grosbeak	Horned Lark
Fox Sparrow	Great Blue Heron	Bushtit	House Sparrow
Golden-crowned Sparrow	Great Egret	California Towhee	Killdeer
Great-horned Owl	Green Heron	California Quail	Northern Rough-winged Swallow
Golden Eagle	Hermit Thrush	Cedar Waxwing	Purple Finch
Greater Roadrunner	House Sparrow	Chipping Sparrow	Snowy Egret
House Finch	Killdeer	Common Raven	Swainson's Thrush
House Wren	Lark Sparrow	Downy Woodpecker	Violet-green Swallow
Loggerhead Shrike	Lesser Goldfinch	Great Blue Heron	
Marsh Wren	Lincoln's Sparrow	Golden-crowned Sparrow	
Northern Flicker	Mourning Dove	Grasshopper Sparrow	
Northern Harrier	Purple Finch	House Finch	
Northern Mockingbird	Rough-legged Hawk	House Wren	
Nuttall's Woodpecker	Rock Wren	Lark Sparrow	
Oak Titmouse	Red-shouldered Hawk	Lazuli Bunting	
Red-breasted Sapsucker	Red-tailed Hawk	Lesser Goldfinch	
Ruby-crowned Kinglet	Red-winged Blackbird	Lincoln's Sparrow	
Ring-necked Pheasant	Say's Phoebe	Loggerhead Shrike	
Sage Thrasher	Savannah Sparrow	Mallard	

Table A2 (continued)

Winter Surveys		Spring Surveys	
Hedgerows	**Controls**	**Hedgerows**	**Controls**
Song Sparrow	Sharp-shinned Hawk	Marsh Wren	
Spotted Towhee	Swainson's Hawk	Mourning Dove	
Tree Swallow	Western Kingbird	Nashville Warbler	
White-breasted Nuthatch	Yellow-billed Magpie	Northern Bobwhite	
White-crowned Sparrow	Yellow-rumped Warbler	Northern Flicker	
Western Bluebird		Northern Harrier	
Western Meadowlark		Northern Mockingbird	
Western Scrub-Jay		Nuttall's Woodpecker	
White-tailed Kite		Orange-crowned Warbler	
		Ruby-crowned Kinglet	
		Ring-necked Pheasant	
		Red-shouldered Hawk	
		Red-tailed Hawk	
		Rufous Hummingbird	
		Red-winged Blackbird	
		Song Sparrow	
		Spotted Towhee	
		Sharp-shinned Hawk	
		Swainson's Hawk	
		Tree Swallow	
		Turkey Vulture	
		White-crowned Sparrow	
		Western Bluebird	
		Western Kingbird	
		Western Meadowlark	
		Western Scrub-Jay	
		Western Wood-Pewee	
		Wild Turkey	
		White-tailed Kite	
		Yellow-billed Magpie	
		Yellow-rumped Warbler	

Table A3. Treatment effects modeled without any other covariates.

Model	Coefficient	Std. Error	p value	p < 0.05
Richness (Winter)	4.50	2.12	0.04	Yes
Richness (Spring)	4.95	2.03	0.02	Yes
Average Abundance (Winter)	0.42	0.03	<2E-16	Yes
Average Abundance (Spring)	0.05	0.03	0.15	No
Loggerhead Shrike (Winter)	1.28	0.36	0.00	Yes
Song Sparrow (Spring)	0.54	0.26	0.04	Yes