Net Impacts of Landscape Change Scenarios

Summary of Task 4 for the project
“Trade-offs and Co-benefits of Landscape Change Scenarios on Bird Communities and Ecosystem Services in the Sacramento-San Joaquin River Delta”

Delta Water Quality and Ecosystem Restoration Program
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Overview

The purpose of this document is to provide a summary of the net impacts of alternate scenarios of landscape change in the Delta developed under Task 4 of our Grant Agreement (Q1996022). The objectives of this task were to (1) with input from partners, identify spatially explicit scenarios of potential landscape change that are current, relevant, and of primary interest to investigate in the Delta, and (2) project the net impacts of each scenario on the provisioning of select ecosystem services and the abundance and distribution of birds in the Delta. This task builds on both the synthesis of ecosystem services indicators completed under Task 2 and the spatial distribution modeling for riparian landbirds, shorebirds, waterfowl, and other waterbirds completed under Task 3. The goals of this task were to develop and demonstrate a general framework for evaluating the multiple benefits and trade-offs of landscape change and provide insights into the likely impacts of alternative scenarios. This task contributes to addressing a science need of **Developing a science-based framework for evaluating co-benefits and trade-offs among multiple goals** and fulfills one of our project’s objectives to **Evaluate the net impact of scenarios of landscape change on bird populations and ecosystem services**. In addition, we will generalize these analyses to develop a flexible, science-based framework for assessing the trade-offs and co-benefits of landscape changes under Task 5 of our Grant Agreement.

Scenario Development

For the purposes of developing and demonstrating a multiple-benefits framework, we required spatially explicit maps of potential future Delta landscapes. Although the historical landscape change and the potential for future landscape change in the Delta is commonly discussed (e.g., Wiens et al. 2016), we found that spatially explicit maps of these potential futures were uncommon; the maps we found were more likely to be maps of risk (e.g., flood risk; DSC 2021a), conceptual drawings (e.g., Delta Conservancy 2019), or designs for individual projects at relatively small spatial scales (e.g., ESA 2019). Therefore, we worked to develop our own spatially explicit scenarios for the Delta, informed by many of these sources, and focusing on scenarios that (1) represented major drivers of potentially significant landscape change in the near term, (2) are likely to have important effects on multiple aspects of the Delta ecosystem, including the abundance and distribution of birds, and (3) could be addressed well within the limitations our existing data and models. For example, limitations in the coverage of waterbird survey data in tidal marsh and open water habitats meant that our current spatial distribution models would not be able to evaluate the impacts of tidal marsh restoration or extensive sea level rise on waterbirds. Although we are developing a generalized, flexible framework that will allow evaluating these impacts when additional data and models become available in the future, our existing spatial models and ecosystem services data developed in Tasks 2 and 3 were better suited to evaluating the impacts of conversions between crop types or conversions between crops and managed wetlands or riparian vegetation. Therefore, with input from staff from California
Department of Fish and Wildlife, Delta Stewardship Council, Delta Conservancy, The Nature Conservancy, Audubon California, Point Blue Conservation Science, and the Central Valley Joint Venture Lands Committee, we selected two drivers of landscape change to investigate further: (1) habitat restoration and (2) perennial crop expansion.

Baseline Landscape

To build a spatially explicit representation of each future scenario, we first developed a map of the baseline landscape intended to represent recent conditions. We started with recently published land cover data that combines classification of NAIP imagery from 2016 with more detailed crop cover data based on imagery from 2014 (CDFW 2019). However, because many agricultural fields were fallowed in 2014 during drought conditions, and to better represent more recent conditions, we overlaid more recent crop cover data based on imagery and crop classifications during the main summer season in 2018 (i.e., “CLASS2”; DWR 2021). We also manually inspected and edited polygons classified as having wetland vegetation. Where small ponds within wetlands were separately classified as open water, we reclassified these ponds as part of the surrounding wetland, and we cross-referenced other wetland mapping efforts including the National Wetlands Inventory (USFWS 2018) and Central Valley managed wetlands (Petrik et al. 2014) to separately classify Tidal Wetland and Managed Wetland from “Other Wetland,” which included polygons that may contain wetland-associated vegetation but are not clearly and intentionally managed as wetlands (e.g., wet meadow). In addition, to reflect the recent and ongoing urban development of the River Islands at Lathrop community (City of Lathrop 2020), and to avoid developing scenarios that would conflict with development plans there, we designated the entire planned residential and commercial areas as Urban in the baseline landscape. Finally, because the spatial distribution models incorporate information about the surrounding landcover up to 10km surrounding each location within the Delta, we filled in a 10km buffer surrounding the Delta boundary with comparable land cover data for the Great Valley Ecoregion to the east (CDFW 2018) and NASS Cropland Data to the west (NASS 2018). We considered our baseline landscape to reflect the Delta landscape as of 2018.

Scenario 1. Habitat Restoration

Habitat restoration is a core strategy for meeting the coequal goals for the Delta (DSC 2020), which include protecting, restoring, and enhancing the Delta ecosystem (Delta Reform Act of 2009), and is also likely to provide multiple additional benefits to society (DSC 2018). We based our habitat restoration scenario on meeting the proposed Delta Plan restoration targets, which include reaching a total of 24,100 acres of non-tidal wetlands and 30,500 acres of riparian vegetation by 2050 (Performance Measure 4.16 in DSC 2020). To develop this scenario, we first accessed restoration project boundaries submitted to EcoAtlas (CWMW 2021), limited to projects within 10km of the boundary of the Legal Delta and those that described restoration in the project goals (i.e., not solely acquisition). We examined the plans for each of these projects
and cross-referenced with maps and additional restoration project descriptions from California EcoRestore (CNRA 2018), including those digitized in the Delta Landscapes Scenario Planning Tool (SFEI 2020), to add additional projects, refine project boundaries, clarify targeted habitat types, and confirm project status. We included in the restoration scenario all restoration projects or portions of projects that were targeting the creation of riparian or non-tidal wetland habitat and were already in-progress or well into the planning stages, such that the target habitat types had been identified (Table S1). We also included in the restoration scenario any projects that were complete by 2021, when we developed this scenario, but not yet complete in 2018, and thus not reflected in the baseline landscape described above (i.e., Sherman Island – Belly Wetland Restoration). We also considered but excluded restoration plans associated with the Delta Wetlands Project, which would convert two islands in the Delta to water storage reservoirs and, as compensatory mitigation, create and enhance wetland habitat on two other Delta islands (ESA 2015), because the restoration scenario would incorporate only the mitigation project and not the reservoir creation they are intended to offset.

We assumed these restoration projects would all be completed as planned, and we summarized the total area of riparian and non-tidal wetland habitat these projects would add within the boundary of the Legal Delta. Because we found that these projects would be insufficient to meet the restoration targets on their own, we further developed the restoration scenario by identifying additional candidate locations for restoration projects across the landscape. We identified candidate locations by first considering areas identified as having the potential to be riparian or non-tidal wetlands (SFEI 2020), and then excluding any of these areas that were already classified as urban in our baseline landscape or were within areas designated for development (DSC 2013). We then classified the remaining candidate locations into groups according to priority level, with the highest priority given to locations within the Delta Stewardship Council’s priority habitat restoration areas (DSC 2020), and particularly those that were also within protected areas or conservation easements (SFEI 2020). We assigned the lowest priority to candidate locations that were already classified as perennial crops in our baseline landscape, assuming these would be the most difficult to convert. We then examined the total area of candidate locations within each priority group and iteratively added candidate locations to the restoration scenario by priority level. If an entire priority level was not required to meet the restoration targets, we grouped candidate locations into contiguous patches and randomly selected entire patches for inclusion in the restoration scenario until the restoration targets were reached or exceeded.

Because the riparian and waterbird spatial distribution models developed in Task 3 included information about subclasses of riparian and wetland land cover, we further specified the type of riparian and wetland restoration these projects represent. We assumed most new non-tidal wetland restoration would result in seasonal managed wetlands, with a hydrology and vegetation similar to existing seasonal managed wetlands throughout the region, except for Sherman Island – Belly Wetland Restoration and Twitchell Island – West End Wetlands, which we assumed would be managed as perennial managed wetlands. For riparian restoration, we
assigned all new riparian restoration patches within areas identified as being suitable for 'willow riparian scrub/shrub' (SFEI 2020) to the ‘Willow Shrub’ subclass used in the riparian species distribution models, and for areas identified as suitable for the more general ‘valley foothill riparian’, we assumed new patches of riparian vegetation would be similar to the composition of riparian vegetation in the surrounding area. Thus, we randomly assigned each patch to a riparian subclass with probability based on the proportion of each subclass found within 2km of the centroid of each patch.

The final restoration scenario includes a combination of real and planned projects with hypothetical future projects, together representing the magnitude and approximate spatial distribution of habitat restoration required to meet the restoration targets. However, we note that this scenario does not necessarily represent the “optimal” locations for maximizing the multiple benefits associated with these restoration projects. Because we recognize that the range of metrics we are currently able to evaluate in this framework is not yet inclusive of all possible values held by members of the Delta community, we have designed this framework to evaluate the potential outcomes of proposed or possible changes to the landscape rather than to prescribe a design optimized for a limited number of metrics.

Scenario 2. Perennial Crop Expansion

The diversity of crops grown in the Delta is high, but recent trends have included a substantial expansion in the extent of perennial crops, particularly almonds, walnuts, and wine grapes, which are replacing annual crops (DPC 2020). Because perennial and annual crops are associated with different ecosystem services and wildlife habitat value (Peterson et al. 2020), these conversions are likely to have an impact on multiple metrics within the Delta ecosystem. We based our perennial crop expansion scenario on recent projections of landscape change throughout the Central Valley (Wilson et al. 2022). This effort developed annual projections for the entire Central Valley under multiple alternative scenarios representing combinations of climate change, management, and restoration, and incorporated an underlying analysis of regional trends in the expansion of perennial crops. We selected the scenario that was primarily driven by perennial crop expansion, which also assumed a relatively moderate warm/wet climate future (over a hot/dry climate), no wetland restoration effort in the Central Valley, and that the recent (1986-2016) high rate of crop conversions continue (i.e., the ‘Bad business-as-usual’ or BBAU scenario). To align with the timeframe of the restoration scenario, we extracted their landscape projections for the year 2050 (Wilson et al. 2021) and retained only the pixels identified as perennial crops within a 10km buffer of the Legal Delta boundary. We overlaid the projected 2050 footprint of perennial crops on the baseline landscape, but because this footprint was developed on a coarser resolution (270m pixels) than the baseline landscape (30m pixels), portions of the projected perennial crop footprint would replace land covers in our baseline landscape that were unlikely to be converted. Thus, we did not allow new perennial crops to replace existing urban, open water, forest, or rice, with the latter excluded because we assumed soils would be unsuitable. However, we did allow perennial crops to replace existing riparian and
wetland land covers if they were not located in protected areas or conservation easements (SFEI 2020).

Due to differences in vegetation structure and phenology, the specific subclass of perennial crop (i.e., deciduous fruit and nut trees, citrus & subtropical, or vineyard) can influence multiple metrics (Peterson et al. 2020), so we specified the specific subclass of perennial crops that would be added to the landscape using a similar process as described above for the restoration scenario. Specifically, we assumed new perennial crops would be similar to the composition of perennial crops in the surrounding area, and we randomly assigned contiguous patches of new perennial crops to a single subclass with probability based on the proportion of each subclass found within 10 km of the centroid of each patch. Thus, the resulting perennial crop expansion scenario represents the extent and approximate spatial distribution of projected perennial crop cover in the Delta if recent expansion trends continue and if new perennial crops are similar in composition to the current proportion of Vineyard, Citrus & Subtropical, and Deciduous Fruits & Nuts. As with the restoration scenario, we again note that this scenario does not necessarily represent the “optimal” locations for maximizing the multiple benefits associated with perennial crop expansion, but rather a hypothetical future to allow evaluation of the potential outcomes.

For each of the three primary landscapes (Baseline, Scenario 1, and Scenario 2), we also generated a winter version specifically for use with the waterbird distribution models developed for the winter season. Because agricultural fields may be double-cropped with two different crops grown during different seasons, the extent and distribution of winter crops may influence the abundance and distribution of waterbirds during the winter. To represent the winter landscape, we again used imagery from 2018, subset to polygons identified as having a distinct early crop (i.e., “CLASS1”; DWR 2021). We then allowed these winter crop types to replace summer crops as long as they represented a compatible change, such as a shift between Grain & Hay, Field Crops, Row Crops, or Grassland & Pasture land cover classes, but not a switch to or from Perennial Crops or Rice. Thus, we produced a total of six landscape maps for analysis: three primary landscapes representing the 2018 baseline and two future scenarios for 2050, and a winter version of each of these.

Scenario Evaluation

To provide a comprehensive understanding of the net impacts of each of the scenarios we developed, we first evaluated the net change in the total area of each major land cover class under each scenario. We then estimated the change in several important metrics as indicators of the health of the Delta ecosystem, including agricultural livelihoods, water quality, climate change resilience, and biodiversity support. To identify these metrics, we reviewed the range of metrics synthesized for land cover types throughout the Central Valley (Peterson et al. 2020) and the Delta Plan Performance Measures (https://viewperformance.deltacouncil.ca.gov), and we identified a set of metrics that were likely of interest to the Delta community and for which
sufficient data were available across land cover classes. We then refined estimates of each metric from Peterson et al. (2020), incorporating additional data and tailoring them to land covers in the Delta to estimate their direct contribution to each of these metrics. Finally, we used the spatial distribution models developed in Task 3 (Dybala et al. 2021) to estimate the change in abundance and distribution of suitable habitat projected for riparian landbirds and waterbirds.

**Agricultural Livelihoods**

Agricultural jobs and economic value are important to maintaining the current way of life in the Delta, and we evaluated the impacts of each scenario on agricultural livelihoods in terms of the number of jobs in the agricultural sector, annual wages to agricultural workers, and gross crop production value. To develop these metrics, we compiled data associated with each land cover class, drawing data on gross crop production value from annual County Agricultural Commissioners’ Reports (CDFA 2015, 2016, 2018a, 2018b, 2020, 2021, 2022) and data on jobs and wages from the Quarterly Census of Employment and Wages (EDD 2022). We extracted annual data for Sacramento, Yolo, Solano, Contra Costa, and San Joaquin counties over 2014–2020, including the annual total crop production value, acreage harvested, number of monthly employees, and their wages by crop class and subclass. For each hectare of each crop class and subclass, we then calculated the average number of employees per month (i.e., full time equivalents, FTE), the average annual wages per FTE, and gross crop production value.

We found no crop production value reported for several land cover classes, including Idle, Urban, Riparian, Managed Wetlands, Other Wetlands, Woodland & Scrub, or Barren, and we assumed a value of $0 per ha per year for each of these. Similarly, we found no reported agricultural jobs or wages associated with these same land covers, as well as Grassland, and we assumed values of 0 employees in the agricultural sector and a corresponding $0 in annual wages per employee. We emphasize that these land cover types are likely to be associated with other forms of economic value and other types of jobs, but here we focused on metrics associated with agricultural livelihoods, which is of high interest to the Delta community and for which substantial data were available.

**Water Quality**

Another important aspect of the health of the Delta ecosystem is the reliability and quality of the water supply. One important factor contributing to water quality is the amount of pesticide runoff into the system, which can affect human health directly by contaminating drinking water or air quality and can affect biodiversity through damaging the aquatic food web. An overall reduction in pesticide runoff is thus expected to contribute to a healthier Delta ecosystem (DSC 2020). As an indicator of risk to water quality from pesticides, we compiled information about the application rates of different chemicals to land covers in the Delta over 2014–2018 (the most recent year available; DPR 2016, 2017, 2018, 2019, 2020). These data are provided by township and section, so we subset the data to the townships and sections within the
Legal Delta boundary and summarized the average pounds of chemicals applied per hectare per year for each landcover class and subclass. However, because many of the chemicals applied are relatively low risk, we included only chemicals that are known groundwater contaminants (DPR 2020), those that pose a “high” or “moderate” risk to aquatic organisms (Lu and Davis 2009), and those listed in the Delta Plan Performance Measures as “critical pesticides” (https://viewperformance.deltacouncil.ca.gov/pm/critical-pesticides). We summarized the combined application rate for all these chemicals, as well as the application rate for each risk group. We found no reports of pesticide use for the landcovers Grassland, Riparian, Wetland, Woodland & Scrub, or Barren, and we assumed the average annual pounds of chemicals applied per hectare was 0 for each of these land cover classes.

Climate Change Resilience

Of increasing concern in the Delta is the need to adapt to climate change, reducing vulnerabilities and increasing resilience (DSC 2021b). Increases in temperature as well as increases in salinity associated with sea level rise and drought conditions are likely to have significant impacts to crop yields and agricultural production (DSC 2021c), with subsequent economic impacts (DSC 2021d), as well as to natural land covers and ecosystem processes (DSC 2021e). However, agricultural crops and natural land cover classes vary in their tolerance of factors like heat, salinity, drought, and flood, and thus vary in how much they contribute to the overall resilience of the Delta ecosystem. We compiled information about the relative resilience (or tolerance) of land cover classes to each of these factors from several sources. We began with climate change vulnerability scores for Central Valley landcovers drawn from a survey of expert opinion (Peterson et al. 2020), which provided an assessment of the relative sensitivity of different land cover classes to heat, drought, and flood, ranging from 1 (low sensitivity) to 3 (high sensitivity). We inverted the sensitivity rankings to instead reflect resilience, such that a high score (3) reflected a higher tolerance. To these data, we added information from several sources about the relative tolerance of different land covers to salinity, especially crop types and pasture (DSC 2021c, Medellin-Azuara et al. 2014), but also wetlands (CDM Smith 2012). We assigned a score of 1 for relatively sensitive, a score of 2 for moderately sensitive/tolerant, and a score of 3 for relatively tolerant land covers. We also compiled information about the relative tolerance of different subclasses of riparian vegetation to drought, flood, and salinity (Fremier et al. 2014). Finally, because we found no assessments for a few additional land cover classes, we assumed Idle and Barren land covers would have a high resilience to all of these factors (score = 3); Woodland & Scrub would have scores equivalent to Riparian; Other Wetlands would have scores equivalent to Grassland; and Urban would have a relatively high resilience to salinity (score = 3), moderate resilience to heat and drought (score = 2), and low resilience to flood (score = 1).
Biodiversity Support

There are many species of fish and wildlife that are valued and of importance in the Delta, including many other bird taxa beyond the riparian landbirds and waterbirds for which we developed spatial distribution models (Dybala et al. 2020). Because developing accurate spatial distribution models requires extensive survey data and analysis effort, we recognize that it is unrealistic to expect to develop models for every species of interest. Thus, we developed a coarse method to evaluate the net impacts of each scenario on support for other taxa of interest. To accomplish this, we applied the avian conservation score developed by a survey of expert opinion (Peterson et al. 2020), which provided an assessment of the relative importance of different land cover classes as habitat for different bird taxa during different seasons, ranging from 0 (no support; not used) to 3 (high support as primary habitat). Taxa assessed included 3 groups of landbirds (those associated with riparian, grassland, and oak savannah habitat) and 3 groups of waterbirds during each of the breeding and non-breeding seasons (waterfowl, shorebirds, and other waterbirds). Although the impacts of each landscape change scenario on riparian landbirds and waterbirds during the fall and winter were separately assessed via their spatial distribution models (described further below), we also included their evaluation via avian conservation score for comparison, as well as used these scores to evaluate the net impacts on grassland and oak savannah landbirds and on breeding waterfowl, shorebirds, and other waterbirds. Because the original assessment did not cover a few additional land cover classes, we assumed: Idle, Barren, and Urban land covers would generally provide no support for any of these taxa; Woodland & Scrub would have provide high support for oak woodland landbirds (score = 3), moderate support for riparian landbirds (score = 2), and low support for grassland landbirds (score = 1); and that Other Wetlands would have scores equivalent to Grassland.

Habitat Suitability

The spatial distribution models developed in Task 3 provide a more detailed method for evaluating the impacts of each scenario on specific species and guilds, including not only information about the total extent of different land cover classes, but also their spatial configuration and proximity to important features on the landscape. The models for riparian landbirds included species-specific breeding distribution models for each of 9 focal species selected by the Central Valley Joint Venture to collectively represent the state of riparian ecosystems in the Central Valley (Dybala et al. 2017), and the models for waterbirds included season-specific models for guilds of waterbird species during the fall and winter portions of the non-breeding season, including dabblers, geese, shorebirds, herons/egrets, cranes, and diving ducks (the latter for the winter season only). All distribution models related the probability of species presence to the extent and configuration of land covers in the surrounding landscape, as well as additional taxon- or guild-specific predictors. To apply these models to the scenarios of landscape change, we first analyzed each landscape to generate the necessary predictors. All models required summaries of the proportion or total area of land cover classes within a range of
distances from each pixel in the Delta: proportion cover within 50m and 2km for riparian landbirds, and total area within 2km, 5km, and 10km for waterbirds. Thus, we generated estimates of the total area of each land cover class within all 4 buffer distances for all six landscapes, then aggregated land cover types according to the different classification schemes used by each set of models (Dybala et al. 2021) and converted to proportion cover for the riparian landbird models.

Waterbird models also required estimates of the proportion of each land cover class that had open water during each season within each of the 2km, 5km, and 10km buffer distances. For the baseline landscape, we used the average probability of open surface water during the fall and winter seasons, 2013–2019, derived from Point Blue’s Water Tracker (Reiter et al. 2018). For each of the scenario landscapes, we assigned a new probability of open water for each pixel that changed land covers from the baseline (i.e., new Riparian or Wetland pixels in Scenario 1, and new Perennial Crops in Scenario 2). We assumed these changed pixels would have a seasonal probability of open water similar to others of the same land cover class, and thus we assigned these changed pixels the mean probability of open water in that land cover class from the baseline landscape. However, in some cases, the new Riparian or Wetland pixels in the restoration scenario were located in areas that already had a higher probability of open water than the baseline mean, so we left these values unchanged. We then generated estimates for the mean probability of open water for each land cover class for each buffer distance, season, and landscape.

An important predictor in the distribution models for cranes was the distance to traditional nighttime roosts (Dybala et al. 2021; Ivey et al. 2015), but ongoing landcover changes since these roosts were mapped, as well as due to each of the future scenarios of landscape change, could affect the suitability of these traditional roost locations. Cranes primarily roost in large open areas with shallow water and little disturbance, which in the Delta includes managed wetlands and post-harvest flooded grain fields (rice, corn, and wheat; Ivey et al. 2016). Therefore, we expected riparian forest and perennial crops to be incompatible with crane roosts, and we examined the overlap of the original roost location polygons with these land covers for each of the landscapes. We included an examination of the baseline landscape primarily due to the ongoing expansion of perennial crops since these roosts were originally mapped. For each landscape, we calculated the proportion of each traditional roost site polygon overlaid by riparian vegetation or perennial crops, excluded any roosts with considerable overlap (>20%), and recalculated the distance to the remaining roosts.

For the riparian landbird models, an important predictor for some species was a metric reflecting the shape of patches of riparian vegetation within 2km of each pixel (McGarigal et al. 2012; Hesselbarth et al. 2019). Because the extent and configuration of riparian vegetation could change in both the habitat restoration and perennial crop expansion scenarios, we recalculated this metric for both landscapes. For two additional riparian predictors, “distance to stream” and “mean annual temperature,” we assumed the landscape changes in each scenario would have no effect, and therefore these predictors remained the same for the baseline and both scenarios.
We used the new predictors derived from each landscape to fit each of the previously-developed spatial distribution models and project the probability of presence for each species or guild across the entire Delta for the baseline landscape and each scenario. For waterbirds, we separately fit the fall models to the 3 primary landscapes and the winter models to the winter versions of each landscape. We fit all models in R (R Core Team 2021) using the R packages dismo and gbm (Hijmans et al. 2020; Greenwell et al. 2020).

Estimating Net Change

To evaluate the net impacts of each scenario across all metrics, we compared the metrics resulting from each scenario landscape to the metrics derived for the baseline landscape. Specifically, for the habitat suitability metrics, we estimated the total area of suitable habitat for each riparian landbird species and each waterbird guild in each season by multiplying the projected probability of presence by the area of each pixel (0.09 ha) and summing over all pixels within the Legal Delta boundary. For the agricultural livelihood and water quality metrics with per-ha values for each landscape, we multiplied by the per-ha metric for each land cover class by the area of each land cover class within the Legal Delta boundary and summed over all land cover classes to represent the total value (e.g., total gross crop production value, total number of agricultural workers, and total pounds of pesticides applied). For the annual wages metric, we further multiplied the average wages per employee for each land cover class by the total number of employees per land cover class and summed over all land cover classes. For the climate change resilience and biodiversity metrics, with unitless rank scores, we multiplied the number of pixels of each land cover class by the rank score for each pixel and summed over all land cover classes. Finally, we calculated the net change and the percent change in each metric between each scenario and the baseline. For the water quality metrics, for which an increase in pesticide application rates would represent an increasing risk to water quality, we reversed the net change and percent change values by multiplying by -1. Thus, for all metrics, we assumed a final net change > 0 would represent a net benefit to the Delta ecosystem and a net change < 0 would represent a trade-off.
Results

Scenario 1. Habitat Restoration

In the development of Scenario 1, we compiled information about restoration projects that were planned or already in-progress (Table S1), and we estimated that these projects would add a total of 1,330 ha of non-tidal wetlands and 393 ha of riparian vegetation within the Legal Delta boundary (Table 1). Added to our estimate in the baseline landscape of 6,009 ha of non-tidal wetland and 8,354 ha of riparian vegetation, we found that the planned and in-progress restoration projects would not be sufficient to meet the proposed Delta Plan restoration targets of 9,753 ha (24,100 acres) of non-tidal wetlands and 12,343 ha (30,500 acres) of riparian vegetation by 2050. To fill the remaining gap, we estimated another 2,414 ha of non-tidal wetland and 3,596 ha of riparian vegetation would need to be restored, for a grand total of 7,733 ha of either land cover class restored.

Table 1. Estimated area (ha) contributed by planned restoration projects, along with additional restoration needed, to meet the proposed Delta Plan restoration targets for 2050 for non-tidal wetlands and riparian vegetation.

<table>
<thead>
<tr>
<th></th>
<th>Non-tidal wetlands</th>
<th>Riparian</th>
</tr>
</thead>
<tbody>
<tr>
<td>Baseline</td>
<td>6,009</td>
<td>8,354</td>
</tr>
<tr>
<td>Planned restoration</td>
<td>1,330</td>
<td>393</td>
</tr>
<tr>
<td>Additional restoration</td>
<td>2,414</td>
<td>3,596</td>
</tr>
<tr>
<td><strong>Total (Objectives)</strong></td>
<td><strong>9,753</strong></td>
<td><strong>12,343</strong></td>
</tr>
</tbody>
</table>

We estimated that there was sufficient area with the potential to be non-tidal wetlands within the Delta Stewardship Council’s priority habitat restoration area (DSC 2020) to meet the restoration target, and that approximately 60% of the remaining gap could be met within areas that were currently within protected areas, conservation easements, and/or public or open space. However, to meet the restoration target for riparian vegetation, we estimated that after excluding areas designated for development, nearly all of the remaining area identified as having the potential to be riparian vegetation would be required, including some areas outside the Delta Stewardship Council’s priority habitat restoration area and areas classified as perennial crops in the baseline landscape.

We found that much of the newly restored non-tidal wetland and riparian vegetation would come from areas classified as Grassland & Pasture in the baseline landscape (2,778 ha; 39%), with the next largest contributors being Row & Field Crops (1,439 ha; 20%) and Idle (1,071 ha; 15%; Figure 1A). If the newly restored riparian vegetation resembles the composition
of riparian vegetation nearby, we estimated that over half (56%) would be Valley Oak-dominated riparian forest, with smaller amounts of Willow Shrub-dominated riparian scrub and Cottonwood-dominated riparian forest (Figure 1B). Finally, we estimated that approximately 80% of the new non-tidal wetlands would be seasonal managed wetlands and 20% perennial managed wetlands, with approximately 556 ha of Other Wetlands converted to Managed Wetlands in this scenario (Figure 1C).

Figure 1. Net change in land cover classes under Scenario 1: Habitat Restoration. (A) Major land cover classes. (B) Riparian subclasses. (C) Wetland subclasses.
We also found that the habitat restoration would be distributed unevenly across the Delta (Figure 2). Approximately half of the riparian restoration would take place in San Joaquin County (2,005 ha), with another 27% in Yolo County (1,085 ha), and 20% in Sacramento County (766 ha). In contrast, over half of the non-tidal wetland restoration would take place in Yolo County (1,964 ha; 61%), with much of the remainder in Sacramento County (1,075 ha; 34%).

**Figure 2.** New areas of Riparian and Managed Wetland restoration added in Scenario 1, shown with county boundaries.
Scenario 2. Perennial Crop Expansion

If recent trends in perennial crop expansion continue through 2050, we estimated the footprint of perennial crops in the Delta would increase by 16,290 ha (Figure 3A). In comparison to the baseline landscape, we estimated this expansion would result in conversions largely from Row & Field Crops (5,623 ha; 35%), Idle (3,527 ha; 22%), Corn (2,450 ha; 15%), and Grassland & Pasture (2,031 ha; 12%) land cover classes. However, it would also include some conversions from Riparian (703 ha) and Wetland (416 ha) land covers not in areas mapped as protected or under conservation easements (SFEI 2020). If the new perennial crops resemble the composition of perennial crops nearby, we estimated the majority would fall in the subclass Deciduous Fruits & Nuts (9,688 ha; 59%), with most of the remainder in Vineyard (6,431 ha; 39%; Figure 3B). In addition, the majority of the increase would occur in San Joaquin County (10,941 ha; 67%), followed by Sacramento County (2,478 ha; 15%) and Yolo County (1,953 ha; 12%; Figure 4).

Figure 3. Net change in land cover classes under Scenario 2, Perennial Crop Expansion. (A) Major land cover classes. (B) Perennial Crop subclasses.
Figure 4. New areas of Perennial Crops added in Scenario 2, shown with county boundaries.
Agricultural Livelihoods

To be able to investigate the potential impacts on agricultural livelihoods of changes in the Delta landscape, we compared the average number of agricultural jobs per 1,000 ha (full time equivalents), average annual wages per employee (in thousands of U.S. Dollars), and the gross crop production value per ha (in millions of U.S. Dollars) across land cover classes (Figure 5). We found substantial variation in the average number of employees across land cover classes, with the highest average numbers per 1,000 ha in Deciduous Fruits & Nuts (180) and the lowest in Hay Farming (0.37). While we did not find any data on the number of employees in the Citrus & Subtropical subclass of Orchards, we assumed it was equivalent to that of Deciduous Fruits & Nuts, and due to the small footprint of this land cover class, we did not expect this assumption to substantially affect our analyses. Similarly, we did not find data specific to Alfalfa, but we assumed it was included in the numbers for Hay Farming. In terms of the average annual wages for these employees, we found the highest averages ranged $42,900–$43,900 in Row Crops, Wheat, Rice, and Pasture, and the lowest average was $33,200 in Vineyard, excluding the land covers for which we assumed no agricultural jobs. Finally, gross crop production values were also highly variable, averaging $0.5 million per 1000 ha in Pasture compared to $10.3 million in Deciduous Fruits & Nuts and $11.1 million in Row Crops. However, we emphasize that these are gross values reported by the County Agricultural Commissioners that do not account for the cost of production and may not account for all sources of income.

Figure 5. Agricultural Livelihood Metrics, 2014–2020. Each metric is scaled differently: Agricultural Jobs reflects the annual average number of agricultural workers per month (i.e., full time equivalents) per 1,000 ha; Annual Wages represents the average total annual wages per agricultural worker (full time equivalent) in thousands of US Dollars; and Gross Crop Production Value represents the value per ha in millions of US Dollars.
Water Quality

As an indicator of the risk to water quality in the Delta, we synthesized pesticide application rates by land cover class, focusing on chemicals that are Critical Pesticides, Groundwater Contaminants, or pose a high or moderate Risk to Aquatic Organisms. Although total application rates cannot account for variation among chemicals in their level of toxicity per pound, or for safety measures taken to prevent exposure to waterways, we assumed that higher application rates pose a higher risk to water quality in the Delta, and therefore a higher risk to human health and the health of the aquatic food web. We found substantial variation across land cover types in the application of these pesticides, as well as variation among the three risk groups (Figure 6). Across all land cover classes in the Delta, chemicals that pose a high or moderate Risk to Aquatic Organisms were more frequently applied, and Groundwater Contaminants were least common. Among both the Critical Pesticides and the Groundwater Contaminants, we found that the highest application rates were in Citrus & Subtropical and Alfalfa land cover classes. Among those that pose a Risk to Aquatic Organisms, we found the highest application rates in Rice, Deciduous Fruits & Nuts, and Row Crops, followed closely by Citrus & Subtropical and Alfalfa. In contrast, application rates were relatively low in any risk group for Grain & Hay, Wheat, and Pasture.

Figure 6. Pesticide Application Rates, 2014 – 2018. Rates are summarized in terms of the total pounds applied per ha per year for all chemicals belonging to each risk group.
Climate Change Resilience

Resilience to climate change includes an ability to withstand extreme events, including drought, floods, and heat waves, as well as a tolerance for longer-term exposure to higher temperatures. In the Delta, rising sea levels in combination with drought and reduced freshwater inflows may also mean increased saltwater intrusion and higher salinity. Evaluating the relative sensitivity or resilience of land cover classes to these threats on a scale of 1–3, we found that none were highly resilient for all threats (score = 3), excluding the Idle and Barren land cover classes for which we assigned a score of 3, and none were highly sensitive for all threats (score = 1; Figure 7). Most land covers had more moderate scores across threats or were mixed, for example with Rice and Managed Wetlands both ranking relatively resilient to flood and salinity but sensitive to drought since they require a substantial water supply. Calculating the average of these scores, we found that Overall resilience was lowest in the three subclasses of Perennial Crops (Deciduous Fruits & Nuts, Vineyard, and Citrus & Subtropical), followed by Row Crops. Again excluding the Idle and Barren land cover classes, the highest Overall scores were in Grassland and Other Wetlands, followed closely by Grain & Hay, Managed Wetlands, Rice, and Riparian.

Figure 7. Climate change resilience. Relative rankings of each land cover class in terms of their resilience (tolerance) to threats expected to increase in frequency or magnitude with climate change: Drought, Flood, Heat, and Salinity. A higher score represents a higher resilience to the threat relative to other land cover classes, and a lower score represents a lower resilience (and higher sensitivity).
Biodiversity Support

As an alternative to developing spatial distribution models for each individual taxon of interest, we adapted an Avian Conservation Score developed from a survey of expert opinion to reflect the relative support to avian conservation provided by different land covers (Peterson et al. 2020). Although the original score was averaged over multiple taxa to assign a single value to each land cover class, here we examined the individual scores for each taxon separately (Figure 8). Taxa are grouped into three rows: landbirds breeding in association with either grasslands, oak Savannah, or riparian habitats; waterbirds during the breeding season, including waterfowl, shorebirds, and other waterbirds; and the same three groups of waterbirds during the non-breeding (winter) season.

Grassland landbirds were most strongly supported by Grasslands, Pasture, and Other Wetlands, while oak savannah landbirds were most strongly supported Woodland & Scrub and Riparian land covers, and riparian landbirds were most strongly supported by Riparian alone. However, several other land cover classes were expected to provide some support to each of these groups, including relatively low support from Perennial Crops for oak savannah and riparian landbirds. No support was expected for any of these landbirds from Field Crops, Corn, or Row Crops.

For all three groups of waterbirds during the breeding season, the highest support was expected from Managed Wetlands and Rice, with additional high support for breeding waterfowl from Grain & Hay, Pasture, Grassland, and Other Wetlands. No support was expected from Corn during the breeding season, but during the non-breeding season Corn provides high support (along with Managed Wetlands and Rice) because it is typically flooded post-harvest in the Delta. Additional support is provided by several other land cover classes during both seasons, including Alfalfa, Riparian, and Other Wetlands. No support is expected for waterbirds during either season from any of the Perennial Crops.
Figure 8. Avian Conservation Score. Relative rankings of each land cover class in terms of the support they provide as habitat for each taxon. Higher scores represent higher support and lower scores represent less support. Scores of zero indicate the land cover class is generally not used by the taxon.
Habitat Suitability

To more closely evaluate the changes in habitat suitability for riparian landbirds and several guilds of waterbirds during the fall and winter portions of the non-breeding season, we developed the predictor variables necessary for fitting each of the spatial distribution models developed in Task 3, and we examined the change in a subset of key predictors that were likely to vary by scenario (Table 2). Examining the proportion cover of Riparian and Wetland land cover classes within 2km of each pixel in the Delta, we found that Scenario 1 resulted in small increases in the mean and maximum values of these metrics compared to the baseline, as well as an increase in the Riparian shape index, which indicates a greater frequency of the rounder, more compact patch shapes associated with less fragmentation instead of long, narrow patch shapes. In contrast, Scenario 2 resulted in a small decrease in the maximum proportion cover of Riparian land cover within 2km, and a small decrease in the mean proportion cover of Wetlands and the mean Riparian shape index. Conversely, Scenario 1 resulted in no change in the proportion cover of Perennial Crops within 2km, but Scenario 2 resulted in an increase in both the mean and maximum.

In examining the overlap of traditional crane roosts with Riparian and Perennial Crop classes, which we assumed were incompatible, we found that the addition of Riparian in Scenario 1 would not overlap with any of the traditional crane roosts, while the addition of Perennial Crops in Scenario 2 would overlap 5 of the traditional crane roost polygons by more than 20%. Therefore, we considered excluded these crane roosts in calculating the distance to roost for each pixel in the Delta, an important predictor of crane presence in the distribution models, resulting in an increase in the mean distance to roost in Scenario 2.

After projecting the probability of presence for each species and guild for each of the two scenarios, we compared them to the probability of presence from the baseline landscape. The resulting “change maps” reflect the complex response of each individual species or guild to each scenario, and indicate where on the landscape the probability of presence has increased or decreased as a result (Figures S1-S6).

Table 2. Summary of the variation by scenario in a subset of key predictors from spatial distribution models.

<table>
<thead>
<tr>
<th>Predictor</th>
<th>Baseline</th>
<th>Scenario 1</th>
<th>Scenario 2</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>mean</td>
<td>(sd)</td>
<td>mean</td>
</tr>
<tr>
<td>Riparian proportion cover within 2km</td>
<td>0.03</td>
<td>(0.04)</td>
<td>0.04</td>
</tr>
<tr>
<td>Wetland proportion cover within 2km</td>
<td>0.07</td>
<td>(0.11)</td>
<td>0.08</td>
</tr>
<tr>
<td>Riparian patch shape index</td>
<td>1.43</td>
<td>(0.22)</td>
<td>1.46</td>
</tr>
<tr>
<td>Perennial crop cover within 2km</td>
<td>0.11</td>
<td>(0.16)</td>
<td>0.11</td>
</tr>
<tr>
<td>Distance to traditional crane roost (km)</td>
<td>7.54</td>
<td>(5.94)</td>
<td>7.54</td>
</tr>
</tbody>
</table>
Net Impacts of Landscape Change Scenarios

For each metric, we summarized the total value or score across all land covers within the Delta for the baseline landscape, and then calculated the difference that would result from each of the two scenarios. Because each metric was calculated in its own units, here we present the results in terms of a percent change from the baseline value. For both scenarios, we identified net changes in opposite directions for the agricultural livelihood and water quality metrics (Figure 9). Under Scenario 1, the restoration of 7,733 ha of Riparian and Managed Wetland land covers, much of which would come from existing agricultural lands (Figure 1), would be expected to reduce the number of agricultural jobs, associated wages, and gross production value, but also reduce the amount of pesticides applied to these lands. In contrast under Scenario 2, the addition of over 16,000 ha of Perennial Crops, which provide some of the highest numbers of agricultural jobs and gross production value (Figure 5), would be expected to result in substantial increases in the numbers of agricultural jobs, associated wages, and gross production value, but also increase the amount of pesticides applied in the Delta.

For Scenario 1, we also found that the restoration of Managed Wetlands and Riparian land covers classes resulted in increasing biodiversity support metrics across most taxa, since one or both of these land covers had high support scores for most taxa (Figure 8). The exception was grassland landbirds, which are expected to have reduced support since the restoration would largely convert from Grassland & Pasture. Similarly, we found little change in the climate change resilience metrics resulting from Scenario 1 since Grassland & Pasture already had relatively high resilience scores compared to Riparian and Managed Wetland land covers (Figure 7). For Scenario 2, the substantial expansion of Perennial Crops was expected to result in a net decrease in all of the climate change resilience scores and a net decrease in biodiversity support scores for most taxa, given the relatively low scores these land covers received. The exceptions in this case were for oak savannah and riparian landbirds, which were each expected to receive low support from perennial crops.

Across all these metrics, the impacts of Scenario 2 were generally larger in magnitude (whether positive or negative) due to the more extensive changes to the landscape in this scenario, with more than twice the number of hectares changing land cover class. However, we noted the relatively substantial changes in biodiversity support metrics resulting from Scenario 1, particularly for breeding shorebirds, breeding waterbirds, and riparian landbirds (Figure 9).
The estimated impact on each metric is reported as the percent change relative to the baseline score. Beneficial changes are shown in blue and trade-offs are shown in orange. Note: For pesticide application rates under Water Quality, we reversed the scores such that a net reduction in pesticide use would represent a benefit to water quality.

The analysis of changes in habitat suitability based on the spatial distribution models generally aligned with the changes in biodiversity support scores for Scenario 1 but provided more detailed information about individual species and seasons (Figure 10). We estimated Scenario 1 would result in increases in the extent of suitable habitat for 8 of the 9 riparian landbird species. In addition, we found increases in the extent of suitable habitat for most of the waterbird guilds during the fall and winter seasons that were larger than the change in biodiversity support metrics suggested for wintering waterfowl, shorebirds, and waterbirds. The exceptions in Scenario 1 were relatively small decreases in suitable habitat for Yellow-breasted Chat and cranes during the winter season. Yellow-breasted Chat is a species with already very low probability of presence throughout much of the Delta (Dybala et al. 2021), and the
distribution model for this species was driven by a combination of the Mixed Shrub and Mixed Forest riparian subclasses along with Grassland & Pasture, suggesting that the conversion of Grassland & Pasture to Managed Wetland and other subclasses of Riparian land cover in Scenario 1 (Figure 1) contributed to the projected reduction in suitable habitat. Similarly, the winter distribution model for cranes was primarily driven by distance to roost, which did not change in Scenario 1 (Table 2), followed by a positive relationship with the extent of flooded corn within 5km, suggesting that the conversion of corn to Riparian and Managed Wetland land cover classes in Scenario 1 contributed to the projected reduction in suitable habitat.

For Scenario 2, the biodiversity support scores suggested an increase in support for riparian landbirds, but the habitat suitability analysis instead resulted in a projected decrease in the extent of suitable habitat for 8 of the 9 focal species. The exception was Spotted Towhee, a species with widespread distribution throughout the Delta (Dybala et al. 2021). The distribution model for Spotted Towhee included, among several other interacting predictors, a negative association with the proportion of Idle land cover within 2km, and a less influential positive association with the proportion of Perennial Crops within 2km, suggesting that the conversion of Idle to Perennial Crops in Scenario 2 contributed to the projected increase in suitable habitat for this species.

Among the waterbirds, the decline in biodiversity support scores for Scenario 2 was generally echoed by the habitat suitability analysis, with declines for most guilds in both seasons. However, we estimated a large increase in the extent of suitable habitat for geese in fall, as well as relatively small increases for geese in winter and cranes in fall. The distribution models for geese in both seasons were primarily driven by the probability of open water at each individual pixel, followed in the fall by a positive relationship with the extent of perennial crops within 10km, and in the winter by a positive relationship with the extent of riparian land cover within 5km. However, we noted that within the Delta, the distribution of riparian and perennial crop land covers are somewhat spatially correlated, likely contributing to uncertainty in their relative influence on the distribution of geese and the unexpected projection of an increase in suitable habitat for geese in Scenario 2.
Figure 10. Net Impacts of Landscape Change Scenarios on Habitat Suitability. The estimated impact on each species is reported as the percent change in suitable habitat relative to the baseline score. Increases are shown in blue and decreases are shown in orange.
Discussion and Future Directions

To effectively plan and implement policies and land management decisions intended to have multiple benefits, it is essential to consider a broad range of community values and be able to identify the potential trade-offs of an action (Gardali et al. 2021). Shifts in the extent and spatial configuration of different land covers are likely to impact many of the goals and values reflected in the Delta Plan, including agricultural livelihoods, water quality, and climate change resilience, in addition to the abundance and distribution of wildlife. Understanding the direction and magnitude of potential changes across so many important metrics remains a key information gap that can limit adaptive management, impede communication and understanding among the Delta community, and contribute to conflict (Wiens et al. 2017; Guaita Martinez et al. 2019). Our analyses laid the foundation for a science-based framework to address this information gap, by developing a set of metrics based on a combination of data collected in the Delta and expert opinion, and establishing transparent, repeatable methods for evaluating their response to alternative scenarios of landscape change.

In this first phase of development, we developed several metrics representing agricultural livelihoods, water quality, climate change resilience, and biodiversity support, in addition to a more detailed analysis of changes in habitat suitability for multiple species. The analysis of these metrics highlighted the potential for synergies between many of the water quality, climate change resilience, biodiversity support, and habitat suitability metrics, and a trade-off with agricultural livelihoods (Figure 9-10). While this result may be intuitive to those with expertise in one or more of these areas, it may not be intuitive to all in the Delta community, and our framework provides a means to communicate these synergies and trade-offs. Further, by quantifying the change in each of these metrics, it becomes possible to consider the relative magnitudes of the costs and benefits in making decisions about policies and plans for land management in the Delta. Importantly, we did not attempt to assign economic value to each of the metrics in this framework. Rather than collapsing each scenario down to a single representation of its net economic value, we think it is essential to transparent decision-making and clear communication to show the impacts of each scenario on the individual metrics, each of which represent individual values held by communities in the Delta.

We find this framework to be a promising approach to support informed decision-making aimed at achieving multiple benefits in the Delta, and we recommend further development in several directions to improve its value and relevance. First, the metrics developed here could be further refined to provide more detailed and comprehensive information. For example, if data about the costs of agricultural production become accessible, they could be incorporated with gross production value to provide a better estimate of the net production value. In addition, we focused our assessment of livelihoods in the agricultural sector, but a more comprehensive evaluation could incorporate information about additional sectors, such as jobs, wages, and economic value related to tourism and conservation in the Delta. Second, we encourage the identification and addition of new metrics to this framework to better represent the broad range
of values important to Delta communities. For example, new metrics could include the relative cultural value or recreational opportunities afforded by different land cover classes or estimates of the net impact to greenhouse gas emissions. New metrics could also include new species of fish and wildlife, such as by developing new spatial distribution models or biodiversity support scores. Third, we developed and evaluated two alternative scenarios for the Delta’s landscape in 2050, but the actual landscape in 2050 is likely to be some combination of the two, along with other landscape changes not yet considered here. These scenarios can be further refined to reflect more likely future landscapes, and entirely new scenarios can be added. For example, due to the lack of data on the use of tidal marsh by the waterbird guilds incorporated in this analysis, and the lack of comprehensive data on the spatial distributions of tidal marsh species, we excluded tidal marsh restoration objectives from Scenario 1, despite the importance of tidal marsh to the health of the Delta ecosystem. An important future extension of this framework will be to incorporate tidal marsh species and an ability to estimate the benefits of tidal marsh restoration.

Finally, some of the results of our analysis were not intuitive, particularly for some of the results of the habitat suitability analysis (Figure 10). The spatial distribution models we developed in Task 3 identified complex relationships between the distributions of each species and guild to the surrounding landscape, allowing projections of their distributions to a transformed future landscape. However, these future projections necessarily carry more uncertainty, particularly where new scenarios result in landscape configurations outside the range of those present in the original data set. For example, the areas of the Delta that are suitable for perennial crops are spatially correlated with the areas that are suitable for riparian vegetation and happen to be close to historical crane roost sites as well. These correlations may introduce uncertainty in the models about the relative influence of each feature of the landscape to the distribution of a species, and therefore introduce uncertainty about projections to future landscapes where these features may no longer be correlated. These uncertainties may be resolved, and models further refined, with additional data collection across a broader range of conditions, either by covering a larger spatial area or by repeated sampling over time as the landscape changes. The Avian Conservation Scores evaluated here provided an alternative and simpler but less detailed approach to estimating the change in support from each scenario. These scores could also be further refined to match survey data and more closely reflect the relative habitat value of individual land cover classes.

The results of these analysis have established a science-based framework for evaluating the co-benefits and trade-offs among multiple goals in the Delta, helping to fill a science need that will facilitate Multiple-Benefit Conservation in the Delta, and fulfilling one of our project’s objectives to evaluate the net impact of scenarios of landscape change on bird populations and ecosystem services. We look forward to continuing to develop this framework further, collaborating with partners in the Delta to incorporate new data, metrics, species, and scenarios. Our goal is to facilitate clearer communication and more inclusive and transparent decision-making that contributes to the long-term vision of a resilient Delta ecosystem with self-sustaining wildlife communities and thriving communities of people.
References


CDM Smith (2012) Salinity Effects on Agricultural Irrigation-Related Uses. Memorandum to CV-SALTS.


Supplemental Material

Table S1. Projects incorporated in the restoration scenario. Projects included those within 10km of the Legal Delta boundary, targeting the restoration of riparian or non-tidal wetlands, not yet complete in 2018 but already in-progress or sufficiently in the planning stage to have a targeted habitat type. For projects designed to restore multiple habitat types, we included only the areas of the project that would restore riparian or non-tidal wetland habitat. Habitat types are listed as the class we assigned, followed by the specific language listed in the source material in parentheses.

<table>
<thead>
<tr>
<th>Project Name</th>
<th>Habitat type(s)</th>
<th>Status</th>
<th>Source(s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bees Lakes Habitat Restoration Project</td>
<td>Riparian (Mixed riparian woodland)</td>
<td>Planning</td>
<td>EcoAtlas, edited to reflect Fig. 5 in Douglas Environmental 2020</td>
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<td>Cosumnes River Acquisition, Restoration Planning, and Demonstration</td>
<td>Riparian (Palustrine wetland: Scrub-shrub riparian)</td>
<td>In-progress</td>
<td>EcoAtlas</td>
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<tr>
<td>Dutch Slough Tidal Marsh Restoration Project</td>
<td>Non-tidal wetland (non-tidal freshwater emergent wetland)</td>
<td>In-progress</td>
<td>EcoAtlas; EcoRestore, as digitized in DSLPT</td>
</tr>
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<td>Grizzly Slough Floodplain Project</td>
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<td>Planning</td>
<td>EcoAtlas; EcoRestore, as digitized in DSLPT</td>
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<td>McCormack-Williamson Tract – North Delta Project</td>
<td>Riparian (Palustrine wetland: Forested and Scrub-shrub riparian)</td>
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<td>EcoAtlas; EcoRestore, as digitized in DSLPT</td>
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<td>Paradise Cut Conservation and Flood Management Plan</td>
<td>Riparian</td>
<td>Planning</td>
<td>EcoAtlas, edited to reflect Fig. 1 in ESA 2019</td>
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<td>Petersen Ranch: Working Waterway Habitat Enhancement Project</td>
<td>Riparian</td>
<td>In-progress</td>
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<td>Sherman Island – Belly Wetland Restoration Project</td>
<td>Non-tidal wetland (non-tidal freshwater emergent wetland)</td>
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<td>Stone Lakes Restoration Project</td>
<td>Non-tidal wetland (Seasonal wetland: managed non-tidal)</td>
<td>Planning</td>
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<td>Three Creeks Parkway Restoration Project</td>
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<td>EcoRestore, as digitized in DSLPT</td>
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<td>Ulatis Creek Arundo Control and Restoration Project</td>
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<td>EcoAtlas</td>
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<tr>
<td>Yolo Flyway Farms Tidal Habitat Restoration Project</td>
<td>Non-tidal wetland</td>
<td>Planning</td>
<td>EcoRestore, as digitized in DSLPT</td>
</tr>
</tbody>
</table>
**Figure S1.** Projected change in habitat suitability from baseline for riparian landbirds under Scenario 1: Habitat Restoration. A positive value (blue) indicates a projected increase in the probability of species presence, and a negative value (red) indicates a decrease.
**Figure S2.** Projected change in habitat suitability from baseline for waterbirds during the fall season under Scenario 1: Habitat Restoration. A positive value (blue) indicates a projected increase in the probability of species presence, and a negative value (red) indicates a decrease.
**Figure S3.** Projected change in habitat suitability from baseline for waterbirds during the winter season under Scenario 1: Habitat Restoration. A positive value (blue) indicates a projected increase in the probability of species presence, and a negative value (red) indicates a decrease.
Figure S4. Projected change in habitat suitability from baseline for riparian landbirds under Scenario 2: Perennial Crop Expansion. A positive value (blue) indicates a projected increase in the probability of species presence, and a negative value (red) indicates a decrease.
Figure S5. Projected change in habitat suitability from baseline for waterbirds during the fall season under Scenario 2: Perennial Crop Expansion. A positive value (blue) indicates a projected increase in the probability of species presence, and a negative value (red) indicates a decrease.
**Figure S4.** Projected change in habitat suitability from baseline for waterbirds during the winter season under Scenario 2: Perennial Crop Expansion. A positive value (blue) indicates a projected increase in the probability of species presence, and a negative value (red) indicates a decrease.