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RESEARCH

Multiple-Benefit Conservation in Practice: A Framework for Quantifying Multi-Dimensional Effects of Landscape Change in California's Sacramento–San Joaquin Delta

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ABSTRACT

Conservation efforts and other land-management decisions are often intended to provide multiple benefits, but real or perceived trade-offs between goals can increase conflict and limit the practice of Multiple-Benefit Conservation. To support decision-making, policy, and management in the Sacramento–San Joaquin River Delta of California, where multiple potentially conflicting goals and values have been identified, we developed a flexible framework for quantifying the benefits and trade-offs that result from landscape change, implemented as an open-source R package. Integrating multiple data sets and methods, we developed metrics that represent (1) agricultural livelihoods, (2) water quality, (3) climate-change resilience, and (4) biodiversity support benefits and then projected the net effects on each metric of three alternative Delta landscapes. Each alternative represented changes that could result by 2050 from meeting habitat-restoration targets in the Delta Plan for riparian and non-tidal wetlands, the continued expansion of perennial crops, or a combination of the two. We found that habitat restoration would provide significant biodiversity support benefits and some climate-change resilience and water-quality benefits without significant trade-offs for agricultural livelihoods, while the continued expansion of perennial crops would provide significant benefits to agricultural livelihoods with simultaneous trade-offs to climate-change resilience and a mix of benefits and trade-offs for water-quality metrics. The combined alternative illustrated the interaction between restoration and perennial crop expansion, with still significant but reduced benefits to both agricultural livelihoods and biodiversity support. Our results provide insights into the effects of each of these drivers of landscape change, alone and in combination, with implications for policy and management to support the practice of Multiple-Benefit Conservation in the Sacramento–San Joaquin River Delta. Our framework serves as a foundation for future collaborative development among scientists, managers, policy-makers, and other interested parties to facilitate evaluation of a more comprehensive set of metrics across new alternative landscapes.

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INTRODUCTION

Conservation efforts are frequently expected to provide multiple benefits, and regional- to continental-scale conservation planning increasingly seeks to provide multiple benefits with their designs (CVJV 2020; United Nations 2020; USDOI et al. 2021; CNRA 2022). As a leading example of landscape management intended to provide multiple benefits, California state law defined two co-equal goals for the management of the Sacramento-San Joaquin River Delta: (1) improving the reliability of the state's water supply and (2) protecting, restoring, and enhancing the Delta ecosystem, while also protecting and enhancing its "unique cultural, recreational, ecological, and agricultural values as an evolving place" (California Water Code § 85054; DSC 2013). The central challenge is how to make progress toward multiple, potentially conflicting goals in a complex landscape while considering the interests and concerns of a large, diverse array of policy-makers, land managers, and community members.

One approach to addressing this challenge and implementing Multiple-Benefit Conservation efforts (*sensu* Gardali et al. 2021) is multi-criteria decision-making and optimization, which is designed to identify one or more landscape-scale solutions that would maximize benefits and/or minimize trade-offs (Fontana et al. 2013; Suddeth Grimm and Lund 2016; Adem Esmail and Geneletti 2018). However, if the suite of metrics considered is incomplete, the "solutions" may be misleading, and in complex landscapes with numerous government agencies and private land-owners making independent management and policy decisions, the likelihood of implementing a coordinated optimal landscape-scale solution may be low. A second approach is to assess the effects of alternative landscapes or scenarios across multiple metrics (e.g., Deverel et al. 2017; Whipple et al. 2022; Vaughn et al. 2024), providing insights into the potential benefits and trade-offs of landscape changes. As an alternative to finding optimal analytical solutions, this approach may more readily facilitate communication of expected trade-offs among scientists, managers, policy-makers, and other interested parties, and thereby facilitate the identification of feasible solutions to offset or minimize such trade-offs (Gardali et al. 2021). With either approach, multiple types of data, models, and methods must be integrated across scientific disciplines and evaluated in a common analytical framework.

To support the practice of Multiple-Benefit Conservation in the Sacramento–San Joaquin River Delta, we developed a flexible open-source analytical framework for projecting and communicating the benefits and trade-offs of alternative landscapes across multiple metrics. We developed the foundations of this framework and demonstrated its use by first developing several example metrics that represented the effects of land-cover change on four benefit categories relevant to California's goals for the Delta: agricultural livelihoods, water quality, climate-change resilience, and biodiversity support. We then projected the net effects on each metric of three example alternative landscapes that represent changes which could result by the year 2050 from meeting habitat-restoration targets in the Delta Plan for riparian and non-tidal wetlands, the continued expansion of perennial crops, or a combination of the two. We then generalized these analyses into an open-source R package to serve as the foundation for incremental progress toward evaluating a more comprehensive set of metrics, new alternative landscapes, or more complex scenarios, as well as to support strong science-based decision-making, policy, and management to make progress toward the Delta Plan's multiple goals.

METHODS

Study Area and Baseline Land Cover

Our study area is defined by the legal Delta boundary. To define baseline land cover within the study area, we adopted a data set recently developed to facilitate the development of bird distribution models in the Delta, which represented the landscape as of 2018 (Figure 1A; Dybala et al. 2023). These data were primarily derived from recently published land cover data (Schwenkler 2019), modified to include crop-cover data from 2018 (CDWR 2018) as well as wetland sub-class detail from other mapping efforts (Petrik et al. 2014; USFWS 2018), and rasterized with 30-m pixels. This baseline land cover data also incorporated land cover within 10 km surrounding the legal Delta, as needed to evaluate some of the metrics described further below.

Benefit Categories and Metrics

We identified four benefit categories relevant to the state's goals for the Delta, within which we identified multiple metrics for inclusion in this analysis. We focused on metrics for which data were readily available for each of the key land cover changes that each of our alternative landscapes represent (described in the next section). This set of benefit categories and metrics is not intended to be comprehensive of all benefits or metrics of interest to policy-makers, land managers, and community members in the Delta, but demonstrates the incorporation of different types of quantitative and qualitative data into a common framework.

Agricultural Livelihoods

Agriculture is a major component of the Delta's economy and culture, and protecting the Delta's unique agricultural values is an objective of the Delta Plan (DSC 2013). To represent agricultural livelihoods in the Delta, we compiled data on agricultural jobs and gross production value associated with individual crop classes over recent years: 2014 to 2020. This time-frame aligned well with the time-frame over which other data were collected for this analysis, especially the bird survey data (described below). Specifically, we extracted data on the annual gross production value and acres harvested in Sacramento, San Joaquin, Yolo, Solano, and Contra Costa counties (CDFA 2022), and mapped crop names to the land-cover classes in our baseline land-cover data. For each land cover, we summarized the total acres harvested and total production value over all counties in each year. Finally, we calculated the mean and standard error for the gross production value per unit area in each year (USD per hectare per year).

Similarly, we extracted data on agricultural employment by county for the same years (CEDD 2022) and mapped industry codes related to crop production (NAICS sector 111) to the land-cover classes in our baseline land-cover data. For each land cover, we summarized the total wages and estimated the total full-time equivalent (FTE) employees as the sum of the average number per month over all counties in each year. We matched the annual employment data to the annual crop production data as calculated above to estimate employees per unit area per year (FTE hectare per year) and their average annual wages (USD per FTE). Employment data were lacking for the crop classes "citrus & subtropical orchards" and "other pasture," so we assumed these would be similar to estimates for "deciduous fruit & nut orchards" and "alfalfa," respectively.

For land covers absent from agricultural employment or gross production value data, we assumed zero agricultural jobs, wages, or production value (Table A2). While natural and developed land covers have other forms of economic value and other types of jobs, these metrics solely represent benefits or trade-offs to the agricultural livelihoods objective of the Delta Plan, and do not replace a comprehensive economic analysis of the direct and indirect effects of a changing landscape, which would incorporate effects on other types of jobs and economic value (e.g., Medellín–Azuara et al. 2012).

Water Quality

Improving water-supply reliability and quality is expected to contribute to a healthier Delta ecosystem and benefit human health (DSC 2013). There are multiple water-quality concerns in the Delta, but among these, changes in land cover may be most likely to influence nitrate levels in groundwater and pesticides in waterways that can affect drinking water and aquatic organisms (DSC 2022a). Although pesticides and nitrogen in Delta waterways may originate outside the Delta (DSC 2013), we focused on rates of pesticide application

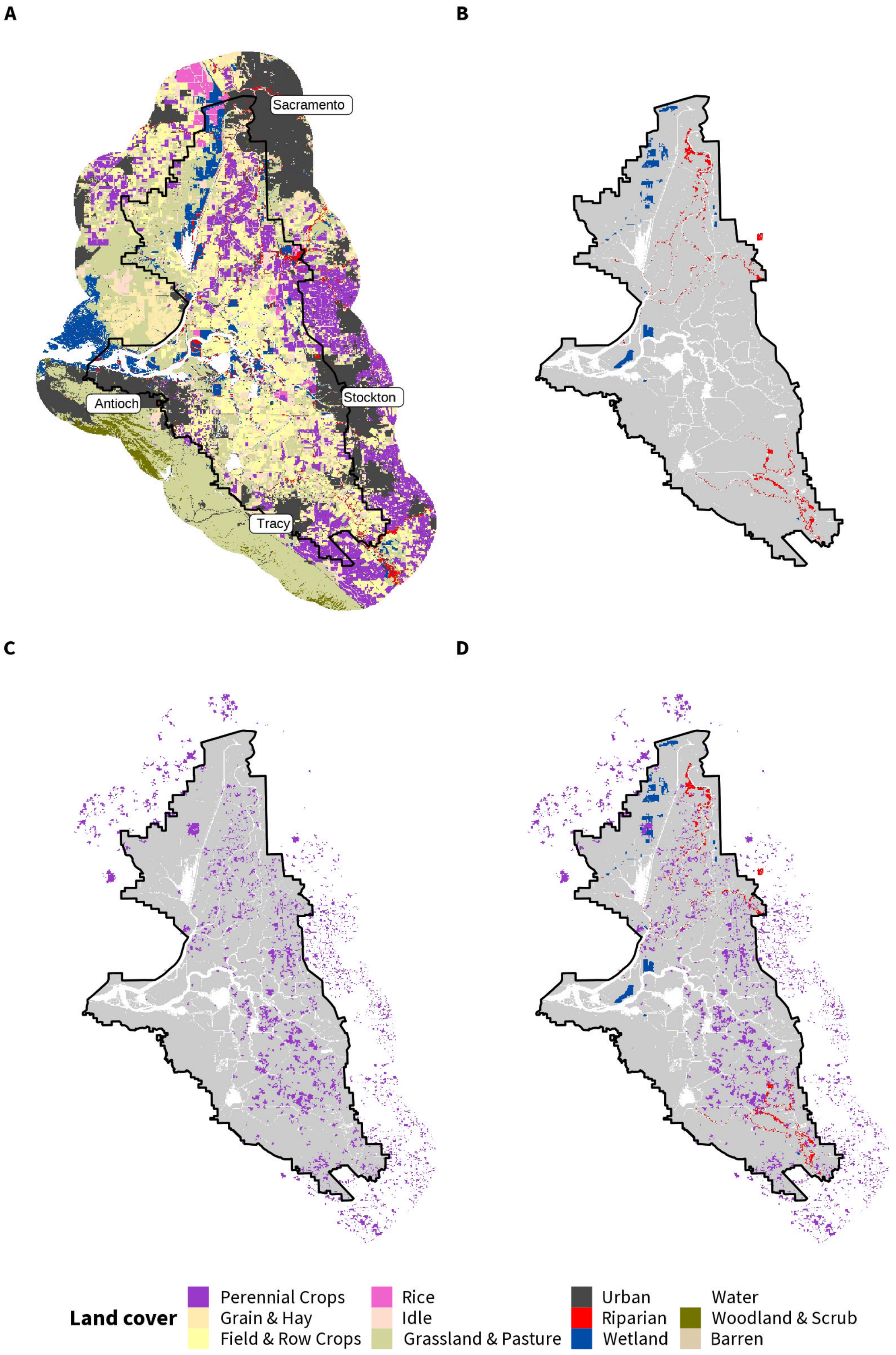

Figure 1 Representations of major land-cover classes in the Delta. (**A**) Baseline as of 2018. (**B**) New areas of riparian and non-tidal wetland added to meet habitat-restoration objectives in AL1. (**C**) New areas of perennial crops added in AL2 to reflect recent rates of expansion. (**D**) AL3, a combination of AL1 and AL2. For each of the alternative landscapes (**B–D**), areas unchanged from the baseline are shown in *gray*, and areas of open water are shown in *white* to aid in orientation.

and nitrogen loading in the Delta as indicators of the risk to Delta water quality associated with each land-cover class.

For pesticides, we compiled lists of chemicals that are known groundwater contaminants (CDPR 2022), pose a "high" or "moderate" risk to aquatic organisms (Lu and Davis 2009), or are designated as "critical pesticides" (DSC 2021a; Table A3). We then compiled information on the application rates of these chemicals in the Delta, from 2014 to 2018 (CDPR 2022) and estimated the mean and standard error for the total annual application rate (kg ha^{-1} yr^{-1}) of each group of chemicals by land-cover class. Where individual land-cover classes were absent from the database (i.e., for "riparian," "wetland," "woodland," "scrub," and "barren" land covers), we assumed zero pesticide application (Table A2). Although total application rates cannot account for variation among chemicals in their level of toxicity per kilogram, or for safety measures taken to prevent their 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.

For nitrogen loading, we extracted crop-specific estimates of the annual rate of potential groundwater nitrogen loading (kg N ha^{-1} yr^{-1}) in the Central Valley from 2005, the most recent year available (Harter et al. 2017). These estimates represent the mass balance after accounting for both the application of synthetic fertilizer and the removal of N through harvest. Where the crop-specific estimates represented a sub-class of the land-cover classes in the baseline landscape, we calculated an average weighted by the proportion of each sub-class in the baseline landscape. For urban areas, we applied the estimated combined, uniform leaching rate of 20 kg N ha^{-1} yr^{-1} (Harter et al. 2017). For "idle" agricultural fields and all other land covers, we assumed zero N loading. As with pesticides, we assumed that higher N loading poses a higher risk to water quality, human health, and aquatic ecosystems in the Delta.

Climate-Change Resilience

The resilience of an ecosystem can be defined as the ability to withstand disturbance and maintain the same core identity, structure, and function (Walker et al. 2004). Distinct from climate-change mitigation efforts—such as restoring aquatic ecosystems to reduce carbon emissions and increase carbon sequestration (Windham–Myers et al. 2023)—climate-change resilience benefits in the Delta ecosystem would mean an improved ability to withstand extreme events, reducing the risk of economic and ecological disasters that could result from drought, floods, and heat waves. Climate change is expected to significantly affect crop yields and agricultural production as well as natural land covers and ecosystem processes (DSC 2021b), likely affecting agricultural livelihoods, water quality, and biodiversity support benefits, in turn.

The presence of more disturbance-tolerant species within more diverse ecosystems and more disturbance-tolerant land covers within more diversified landscapes are associated with climate-change resilience (Timpane–Padgham et al. 2017; Beller et al. 2019; Nelson et al. 2022). Therefore, we expected the overall climate-change resilience of the Delta ecosystem to increase with a greater diversity of land covers, and with more land covers that were relatively tolerant of climate stressors. We defined an overall landscape diversity score as the Shannon index calculated from the number of hectares of each land-cover class (Nagendra 2002), and we also drew on several qualitative assessments of the relative tolerance or sensitivity of each land cover to drought, flood, and heat (Peterson et al. 2020; DSC 2021b). We re-scaled these assessments to align them on a scale of 10 (high tolerance) to 1 (low tolerance), and calculated the mean and standard error of the scores for each land-cover class. Several land-cover classes were absent from these scores ("urban," "idle," "barren," "tidal wetland," and "woodland & scrub"), and we assigned scores that reflected our own assessment (Table A2).

Biodiversity Support

As part of a large estuary on the Pacific coast of the Americas, with a diversity of intersecting land covers and waterways, the Delta provides habitat to hundreds of species of plants, fish, and wildlife (Dybala et al. 2020; DSC 2021b). To reflect this species diversity and their habitat needs, a comprehensive estimate of biodiversity-support benefits should include numerous species across multiple taxa, but during this foundational stage of developing a framework for Multiple-Benefit Conservation, we focused on benefits for a suite of bird species. The Delta provides valuable habitat to a large and diverse community of resident and migratory birds (Dybala et al. 2020) and providing bird habitat is one of the goals for protecting, restoring, and enhancing the Delta ecosystem (California Water Code § 85302€; DSC 2022b). To estimate biodiversity-support benefits for a suite of birds, we relied on recently-developed distribution models for nine riparian landbird species during the peak of breeding season (May to June) and six groups of waterbirds, collectively representing 46 species, during the fall (July 15 to November 15) and winter (November 17 to March 5) seasons (Dybala et al. 2023). To apply these distribution models to each alternative landscape, we first developed new predictor metrics for each pixel in the landscape; many of the model predictors represented the amount of each land-cover class, summarized over the area within each of several distances of the pixel: the proportion cover within 50 m and 2 km for riparian landbirds, and the total area within 2 km, 5 km, and 10 km for waterbirds.

For waterbirds, predictors also included estimates of the baseline proportion of each land-cover class that had open surface water during each of the fall and winter seasons, based on the observed 2013 to 2019 average probability of open surface water during each season derived from Point Blue's Water Tracker (Reiter et al. 2018). We assumed no change in the probability of open surface water under each alternative landscape, except for pixels that had changed land-cover class, to which we assigned the mean probability of open surface water for the new class. For cranes, the distance to nighttime roosts was also an important predictor of suitable foraging habitat (Ivey et al. 2015; Dybala et al. 2023). Because crane roosts are typically large open areas with shallow water and little disturbance, including managed wetlands and post-harvest flooded grain fields (Ivey et al. 2016), we expected the presence of riparian forest and perennial crops to reduce the suitability of existing crane roosts. For each alternative landscape, we calculated the proportion of known roosts, mapped from 2007 to 2009 (Ivey et al. 2016) with additions to this dataset made by The Nature Conservancy (The Nature Conservancy and G. Ivey, 2015, unpublished, see "Notes"), that would be overlaid by newly added riparian vegetation or perennial crops. We assumed known roosts with considerable overlap (>20%) would become unsuitable under that alternative landscape, and we therefore recalculated the distance of each pixel to all remaining roosts.

Development of Alternative Landscapes

With input from local agencies and organizations, we identified habitat restoration and continued perennial crop expansion as two major, potentially conflicting drivers of landscape change in the Delta. We developed three alternative landscapes (ALs) that represented the expected magnitude and approximate spatial distribution of changes to the baseline landscape that could result by the year 2050 if:

1. habitat-restoration efforts succeed in meeting objectives in the Delta Plan for riparian and non-tidal wetlands,
2. perennial crops continue to expand at recent rates, or
3. a combination of both occurs.

To isolate how each of these drivers would affect the benefit categories, we assumed no concurrent changes in any other environmental conditions (e.g., climate, salinity, or sea level rise), no changes in the typical land management applied to each land-cover class, and no changes in the typical quality or condition of each land-cover class over this time-frame. Thus, rather than serving as realistic and comprehensive scenarios of the future Delta landscape in 2050, these alternative landscapes serve to demonstrate how our framework can improve understanding of the relationship between individual drivers of landscape change and the magnitude of their expected benefits and trade-offs.

Alternative Landscape 1: Habitat Restoration

Habitat targets in the Delta for the year 2050 include reaching a total of 9,753 ha (24,100 acres) of non-tidal wetlands and 12,343 ha (30,500 acres) of riparian vegetation, among targets for other ecosystem types, notably tidal wetlands (21,206 ha; 52,400 acres; DSC 2022a). However, in AL1 we did not address tidal wetlands or all of these other targets because we lacked comparable data to represent the biodiversity-support benefits for each, and we wanted to avoid under-representing their benefits. Tidal wetland restoration will be incorporated in future phases of framework development as these data become available.

Restoring non-tidal wetlands and riparian vegetation to meet these targets is expected to provide benefits to biodiversity support but will likely require conversion of agricultural lands and the loss of some benefits to agricultural livelihoods. Therefore, to represent an alternative landscape in which these restoration targets have been reached, we first estimated the total area of riparian vegetation (all sub-classes) and non-tidal wetlands (i.e., perennial and seasonal managed wetlands) in the baseline landscape (Figure 1A; Dybala et al. 2023). We excluded "other wetlands," which were areas classified as having wetland vegetation but not clearly managed as wetlands. We then compiled shapefiles that represented known planned and in-progress riparian and non-tidal wetland restoration projects within the legal Delta boundary and the surrounding 10 km (CNRA c2018; SFEI 2020; CWMW 2021; Table A1). Although we did not consider projects outside the legal Delta boundary as contributing to the restoration targets, we wanted to account for their potential influence on biodiversity support in the surrounding areas. Accounting for both existing and planned restoration of riparian vegetation and non-tidal wetlands, we estimated that additional restoration projects were still needed within the legal Delta boundary to meet the restoration targets. Therefore, we then identified candidate locations for additional future projects from areas previously identified as having an appropriate location and elevation for riparian or non-tidal wetlands (SFEI 2020). We excluded candidate locations in areas mapped as "urban" land cover or designated for development (DSC 2013) and assigned the remaining candidate locations to priority groups based on combinations of: (1) location within a Priority Habitat Restoration Area (highest priority; DSC 2022b); (2) public land or open space (second priority; DSC 2013); (3) protected areas or conservation easements (third priority; SFEI 2020). We also considered candidate locations in the baseline landscape that were mapped as perennial crops to be the lowest priority. To complete AL1, we selected all members of a priority group until the entire group was not required to meet the restoration targets. We then randomly selected contiguous patches of candidate locations from the next priority group that were at least 0.4 ha (1 acre) in size until the restoration targets were met or exceeded. Thus, AL1 represents the magnitude and spatial distribution of landscape change in the Delta by 2050 that could result from efforts to meet the habitat-restoration targets for riparian and non-tidal wetlands (Figure 1B).

For use with the distribution models described above, we further refined AL1 by assigning riparian and wetland sub-classes to all restored areas. For non-tidal wetlands, we assigned all new pixels to the seasonal managed wetland sub-class except for planned and in-progress wetland restorations that specified perennial wetlands as the target. Seasonal managed wetlands are more prevalent throughout the Central Valley and Delta, including in the Priority Habitat Restoration Areas where all randomly-selected future wetland restoration locations were distributed, but perennial managed wetlands may be more likely for wetland-restoration projects in the Central Delta, where goals often include limiting carbon emissions and slowing or reversing subsidence (Windham–Myers et al. 2023; Vaughn et al. 2024). For riparian vegetation, the baseline landscape included seven sub-classes, including: “Fremont cottonwood alliance,” “valley oak alliance,” “willow alliance,” and “willow shrub alliance.” The remaining three sub-classes include: “mixed forest” and “mixed shrub,” which describe tree- and shrub-dominated riparian vegetation, respectively, that did not fall into any of these other sub-classes; “introduced riparian scrub” describes areas dominated by non-native species (see Dybala et al. 2023 for details). Of these, “valley oak,” “willow shrub,” and “Fremont cottonwood alliances” are the most abundant in the baseline landscape. For riparian restoration in areas identified as having an appropriate location and elevation for “willow riparian scrub/shrub” (SFEI 2020), we assigned them to the “willow shrub” sub-class; for all other areas identified as suitable for the more general “valley foothill riparian,” we randomly assigned contiguous patches to a sub-class (excluding “introduced riparian scrub”) with probability based on the proportion of each sub-class found within 2 km—the same spatial scale used in the development of the riparian distribution models (Dybala et al. 2023).

Alternative Landscape 2: Perennial Crop Expansion

Between 2009 and 2016, perennial crops expanded in the Delta, particularly almonds (401% increase) and wine grapes (38% increase; DPC 2020). Because perennial crops, especially wine grapes, are among the most valuable agricultural products in the Delta (DPC 2020), expansion of perennial crops may provide some benefits to agricultural livelihoods, especially gross production value. However, the conversion of more wildlife-friendly crops to perennial crops is likely to produce a trade-off with some biodiversity-support benefits (Shuford et al. 2019; Peterson et al. 2020). Therefore, to represent an alternative landscape in which the recent rates of perennial crop expansion continue, we used recently developed projections of the future footprint of perennial crops in 2050, which were based on an assumption that recent regional conversion rates from other agricultural land covers continue (BBAU scenario; Wilson et al. 2021, 2022). We overlaid this footprint on our baseline landscape, but to refine the coarser resolution of this projected footprint (270-m pixels), we did not allow new perennial crops to replace existing “urban” or “open water” land covers (e.g., lakes, rivers) or existing land covers within protected areas and conservation easements. Alternative Landscape 2 may still over-estimate the potential expansion of perennial crops because the original projected footprint did not restrict crop conversions to areas with suitable soil conditions or water supply, and changes in salinity and the frequency of flooding associated with sea level rise may further limit perennial crop expansion in the Delta (DSC 2021b). Thus, we considered AL2 to represent the upper limit for the magnitude and approximate spatial distribution of landscape change that could result by 2050 from perennial crop expansion (Figure 1C).

Because many of the metrics and their data sources described above distinguished among sub-classes of perennial crops, we assigned all new perennial crops to one of “deciduous fruit & nut orchards,” “citrus & subtropical orchards,” or “vineyards” sub-classes. We randomly assigned each contiguous patch of new perennial crops to one of these sub-classes, with probability based on the proportion of each sub-class found within 10 km—the spatial scale necessary to ensure coverage for all new patches of perennial crops.

Alternative Landscape 3: Combination

We found it useful to estimate the independent effects of habitat restoration and perennial crop expansion on multiple benefit categories through AL1 and AL2, but both drivers of landscape change will operate simultaneously, along with other landscape changes not considered here. To estimate the extent to which the combined effects of these two drivers of landscape change will amplify or nullify each other, we also evaluated a third AL that represented a combination of both. In AL3, we ensured the restoration objectives would still be met by overlaying the projected footprint of perennial crops on the baseline, as in AL2, but this time ensuring new perennial crops did not replace any existing riparian or managed wetlands. We then overlaid the full set of planned, in-progress, and proposed additional restoration projects developed for AL1, allowing them to override any projected expansion of perennial crops in the same location. Thus, AL3 combines all riparian and wetland land covers included in AL1 with a slightly smaller footprint of perennial crops from AL2 (Figure 1D).

Evaluation of Alternative Landscapes

To evaluate the net effects of each AL on each benefit category and metric, we first developed total landscape scores for each of the metrics in the agricultural livelihood, water quality, and climate-change resilience categories (S_{mL}). For most of these metrics, we calculated S_{mL} as the sum total of the estimates for each land-cover class multiplied by the area of each land-cover class:

$$S_{mL} = \sum_{i=1}^{n} m_i * A_{Li} \qquad \text{Eq 1}$$

where m_i is the per-ha estimate for each metric m in each land-cover class i (Table A2), n is the number of land-cover classes, and A_i is the total area (ha) of each land-cover class in the Delta in landscape L. Wherever possible, we estimated the uncertainty in each S_{mL} (u_{smL}) by using standard error-propagation methods:

$$u_{smL} = \sqrt{\sum_{i=1}^{n} (u_{mi} * A_{Li})^2} \qquad \text{Eq 2}$$

where u_{mi} is the standard error in each of the underlying estimates of m_i (Table A2). To estimate the new average annual wage of agricultural employees for the entire landscape, which was based on the annual average by land-cover class, we replaced A_{Li} in the equations above by the proportion of each land-cover class in the landscape. For the climate-change resilience scores that represented drought, heat, and flood tolerance, we divided S_{mL} by the total area of the landscape to estimate the per-ha average score. We also calculated the landscape diversity score as the Shannon index of the number of hectares of each land-cover class (Nagendra 2002; Oksanen et al. 2022).

From the total landscape scores for each metric, we then calculated the net effect of each AL on each metric (d_{mL}) as the difference between S_{mL} for each AL and the corresponding score for the baseline landscape (S_{mB}):

$$d_{mL} = S_{mL} - S_{mB} \qquad \text{Eq 3}$$

Wherever possible, we estimated the uncertainty in each d_{mL} as the square-root of the sum of the squared u_{smL}. However, we then doubled this estimate and followed established methods to estimate expanded uncertainty (U_{smL}) with a coverage factor $k = 2$; this approach defines an interval expected to encompass a large fraction of the distribution of values, approximating a 95% confidence interval (BIPM et al. 2008). For landscape diversity scores, we calculated d_{mL} after first taking the exponent of the Shannon indices, and we used Hutcheson's t-test to estimate the statistical significance of the differences between Shannon indices (Salinas and Ramirez–Delgado 2021).

We separately evaluated the net effect of each AL on biodiversity support by fitting each of the distribution models to the predictors derived from each AL in R (R Core Team 2023) using the R packages 'dismo' and 'gbm' (Greenwell et al. 2020; Hijmans et al. 2020). We converted the resulting predictions of the probability of presence into binary predictions of presence or absence using thresholds that ensure each model's sensitivity (true positive rate) is equal to specificity (true negative rate), an approach that has performed well in simulation experiments (Liu et al. 2005). To represent the total biodiversity support provided by each landscape for breeding riparian landbirds and for waterbirds during the fall or winter season, we summed the total area over which at least one bird species or group in each set was predicted to have suitable habitat. As described above for the other metrics, we calculated the net effect of each AL (d_{mL}) on the total area of suitable habitat for each bird species and group, and we estimated the uncertainty in d_{mL} using a bootstrap resampling approach (Leathwick et al. 2006). We resampled the original bird survey data for each model 50 times, fit a boosted regression tree model to each sample, predicted the total amount of suitable habitat for each landscape from each model, and estimated d_{mL}. We then used the 2.5 and 97.5 percentile values for the bootstrap estimates of d_{mL} as an estimate of the 95% confidence interval.

To interpret the net effect of each AL on each metric in a common framework, we reversed the sign of d_{mL} for the water-quality metrics (multiplying by –1) so decreased pesticide application or nitrogen loading rates would result in an increase in water-quality benefits. Thus, for all metrics, $d_{mL} > 0$ represents a net benefit to the Delta ecosystem and $d_{mL} < 0$ represents a trade-off. In addition, for all metrics, we considered d_{mL} to represent a *statistically* significant change from baseline conditions if the estimated confidence interval did not overlap zero or if the Hutcheson's t-test indicated a significant difference in Shannon indices ($p < 0.05$). We also considered d_{mL} to represent a *practically* significant change for the Delta ecosystem if it represented at least a 5% change from baseline conditions.

To support the reproducibility of our analyses and their extension to new metrics, models, data sources, and alternative landscapes, we developed the customized R package '`DeltaMultipleBenefits`' (Dybala 2023). The package contains a vignette that illustrates the use of functions for preparing a new AL, applying existing metrics and distribution models to the new AL, and calculating the net effect. Users can also readily incorporate custom metrics and models in their own analyses by following the examples provided.

RESULTS

Benefit Metrics

For metrics that represented agricultural livelihoods, we identified the three highest average annual gross production values in "deciduous fruit & nut orchards," "row crops," and "vineyards" ($12.6, $12.3, and $11.0 thousand per ha, respectively), which also employed the most people per 100 ha (5.10, 4.97, and 2.27 FTE, respectively), but offered some of the lowest average annual wages per FTE (< $37,100; Table A2). However, the range of average annual wages per FTE was narrow, with the highest values in wheat ($40,985) and hay farming ($41,925). Our estimates of gross production value and employment were broadly comparable to previous estimates of revenue and employment by crop class, despite differences in data sources and crop class groupings (Medellín-Azuara et al. 2012).

Representing water quality, pesticide application rates across all land-cover classes in the Delta were generally highest for the group of chemicals identified as posing a "high" or "moderate" risk to aquatic organisms; within this group, the highest average application rates were in "rice," "deciduous fruit & nut orchards," and "row crops" (7.31, 6.20, and 5.97 kg ha^{-1} yr^{-1}, respectively; Table A2). In comparison, the highest application rates of chemicals in the critical pesticides and groundwater contaminants groups were in "citrus & subtropical orchards", at rates less than half of these (2.82 and 0.67 kg ha^{-1} yr^{-1}, respectively). Reported pesticide application rates were relatively low in any pesticide group for "wheat," "other grains," and "other pasture," as well as "idle" fields and "urban" areas. We found no reported pesticide application in any of the other non-agricultural land-cover classes. The highest rates of potential groundwater nitrogen loading were in "corn," "other field crops," and "grain & hay" (320, 223, and 195 kg N ha^{-1} yr^{-1}, respectively; Table A2). The lowest rates were in "rice," "urban," and "pasture" (19, 20, and 30 kg N ha^{-1} yr^{-1}, respectively), although harvest rates in pasture—and therefore nitrogen loading rates—were reported as relatively uncertain in the original analysis (Harter et al. 2017). No estimates of uncertainty in these rates were reported, and therefore we did not estimate uncertainty in the effect of each AL on N loading.

In terms of climate-change stressors, none of the land-cover classes or sub-classes were ranked highly sensitive (score < 2.5) to all stressors considered, and the only land covers ranked as highly tolerant (score > 7.5) to all stressors were the sub-class "grassland" and the classes to which we assigned high scores: "idle" and "barren" (Table A2). Most land covers instead had more moderate scores or mixed scores, indicating tolerance of some climate-change stressors and sensitivity to others. For example, "managed wetlands" were considered tolerant of heat and flood but not drought, while "wheat" and "other grains" were considered tolerant of heat and drought but not flood.

For biodiversity support, the results of the distribution models are described in Dybala et al. (2023), but briefly, the distributions of each taxon were influenced by unique combinations of local land cover and the composition of the surrounding landscape (ranging 2 to 10 km). The distributions of all riparian landbird species during the breeding season were influenced by the extent of riparian vegetation, but with varying associations to different riparian sub-classes, and additional influences of wetland cover and distance to stream channel. The distributions of waterbird groups during the non-breeding season were influenced by the extent of surface water on the surrounding landscape, varying by land-cover class and between fall and winter portions of the non-breeding season.

Changes in Land Cover Under Alternative Landscapes

In AL1, we estimated that planned and in-progress restoration projects would add a total of 1,330 ha of non-tidal wetlands and 393 ha of riparian vegetation within the Delta to our estimate in the baseline landscape of 6,009 ha of non-tidal managed wetland and 8,354 ha of riparian (Table 1). Thus, another 2,414 ha of non-tidal managed wetland and 3,596 ha of riparian would need to be restored by 2050 to meet restoration targets. To fill this remaining gap for non-tidal wetlands, there was sufficient area suitable for restoration within the Priority Habitat Restoration Areas, and we prioritized candidate locations within these areas, which excluded the most subsided areas in the central Delta (Figure 1B). For additional candidate riparian restoration projects, after excluding areas designated for development, nearly all areas suitable for riparian restoration would be required to meet the restoration target, including locations outside the Priority Habitat Restoration Areas and locations classified as perennial crops in the baseline landscape. The final restoration AL resulted in a 48% increase in riparian land cover and a 16% increase in the total area of wetlands relative to the baseline landscape, including a 125% increase in perennial managed wetlands and a 51% increase in seasonal managed wetlands. The land-cover class that contributed the largest proportion to these restorations (meaning a reduction in total area) was "grassland & pasture" at –5% (Figure 2).

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

	Non-tidal wetlands	Riparian
Baseline area	6,009	8,354
Planned restoration	1,330	393
Additional restoration needed	2,414	3,596
Total area added to baseline	3,744	3,989
Total (objectives)	**9,753**	**12,343**

For AL2, if recent trends in perennial crop expansion continue through 2050, the footprint of perennial crops within the Delta could increase by as much as 16,214 ha, a 50% increase over the baseline area (Figure 2). This alternative would require crop conversions primarily from "field & row crops" (6,025 ha), "grassland & pasture" (3,494 ha), and "idle" (3,473 ha). However, it would also include some conversions from "riparian" (703 ha) and "wetlands" (407 ha) not in areas mapped as protected or under conservation easements.

In AL3, the net change in "riparian" and "managed wetland" covers matched those of AL1, while perennial crops increased by 14,288 ha—a 44% increase over the baseline area (Figure 2). This increase was smaller than that of AL2, because we did not allow perennial crops to replace any existing "managed wetland" and "riparian" land covers in the baseline to ensure restoration targets were met, and because restoration of riparian vegetation took precedence in locations that might otherwise be converted to perennial crops. Similar to AL2, we estimated

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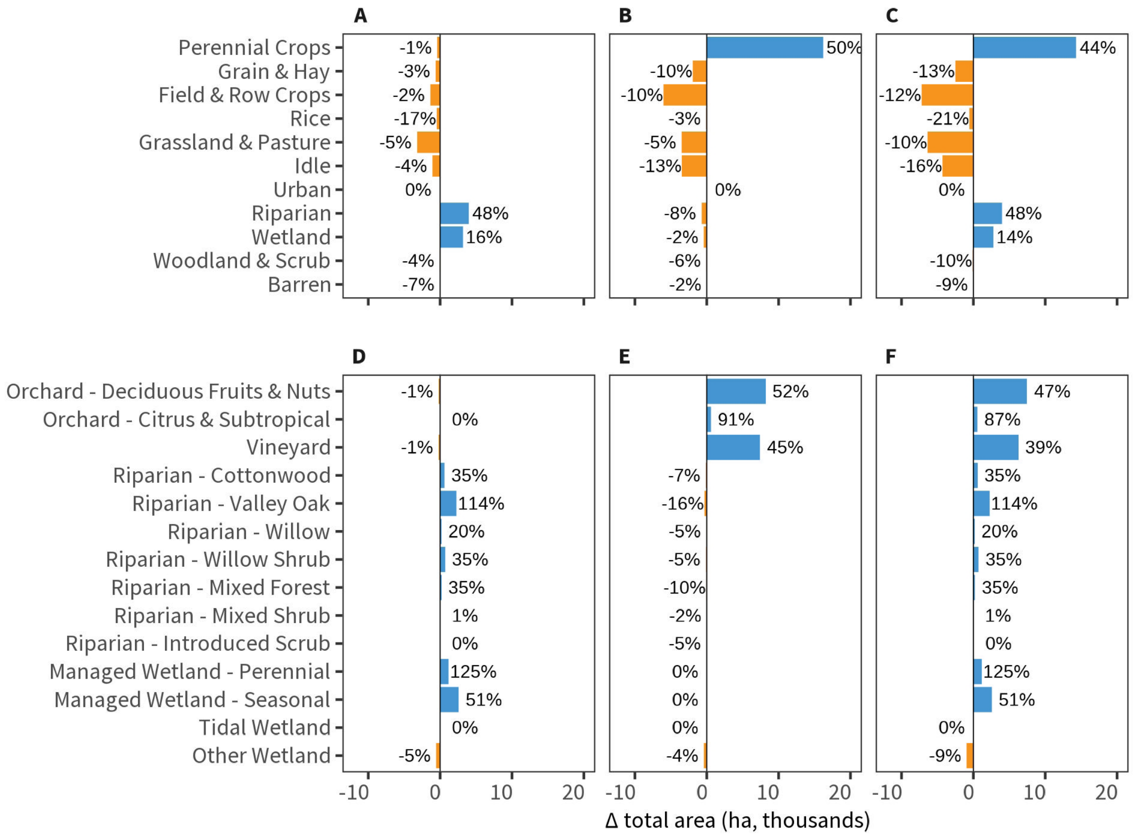

Figure 2 Net effects of each alternative landscape on land cover for major land-cover classes (**A–C**) and select sub-classes (**D–F**). (**A**, **D**) AL1: Habitat restoration. (**B**, **E**) AL2: Perennial crop expansion. (**C**, **F**) AL3: Combination. Each *bar* represents the change in the total area of each land-cover class relative to the baseline, shown in thousands of ha, along with the percent change. Net increases are shown in *blue* and net decreases are shown in *orange*.

that AL3 would result in losses primarily of “field & row crops” (7,199 ha), “grassland & pasture” (6,379 ha), and “idle” (4,301 ha).

Changes in Benefit Metrics under Alternative Landscapes

Under AL1, we estimated biodiversity-support benefits that were both statistically and practically significant (i.e., confidence intervals [CIs] did not overlap zero and > 5% change from baseline; Figure 3). For riparian landbirds, we estimated a statistically significant increase of 5,995 ha of suitable habitat (95% bootstrap CI: 2,639–12,747; + 3% from baseline), and for waterbirds, we estimated statistically and practically significant increases in suitable habitat of 3,877 ha during the fall (95% bootstrap CI: 2,454–5,954; +16% from baseline) and 3,844 ha during the winter (95% bootstrap CI: 1,219–5,750; + 7% from baseline) (Table 2). Further, the direction of the projected net effects for individual species and groups were positive for all but cranes during the winter season (Figure 4). We also found a statistically (but not practically) significant increase in climate-change resilience benefits in terms of landscape diversity ($p < 0.001$), and a potential water-quality benefit in terms of reduced N loading to groundwater, although we could not evaluate statistical significance because of the lack of underlying uncertainty estimates. We found no evidence for statistically or practically significant effects of restoration projected for any agricultural livelihood metrics, pesticide application rates, or resilience to drought, heat, or flood—all of which had CIs overlapping zero with < 5% difference from baseline conditions.

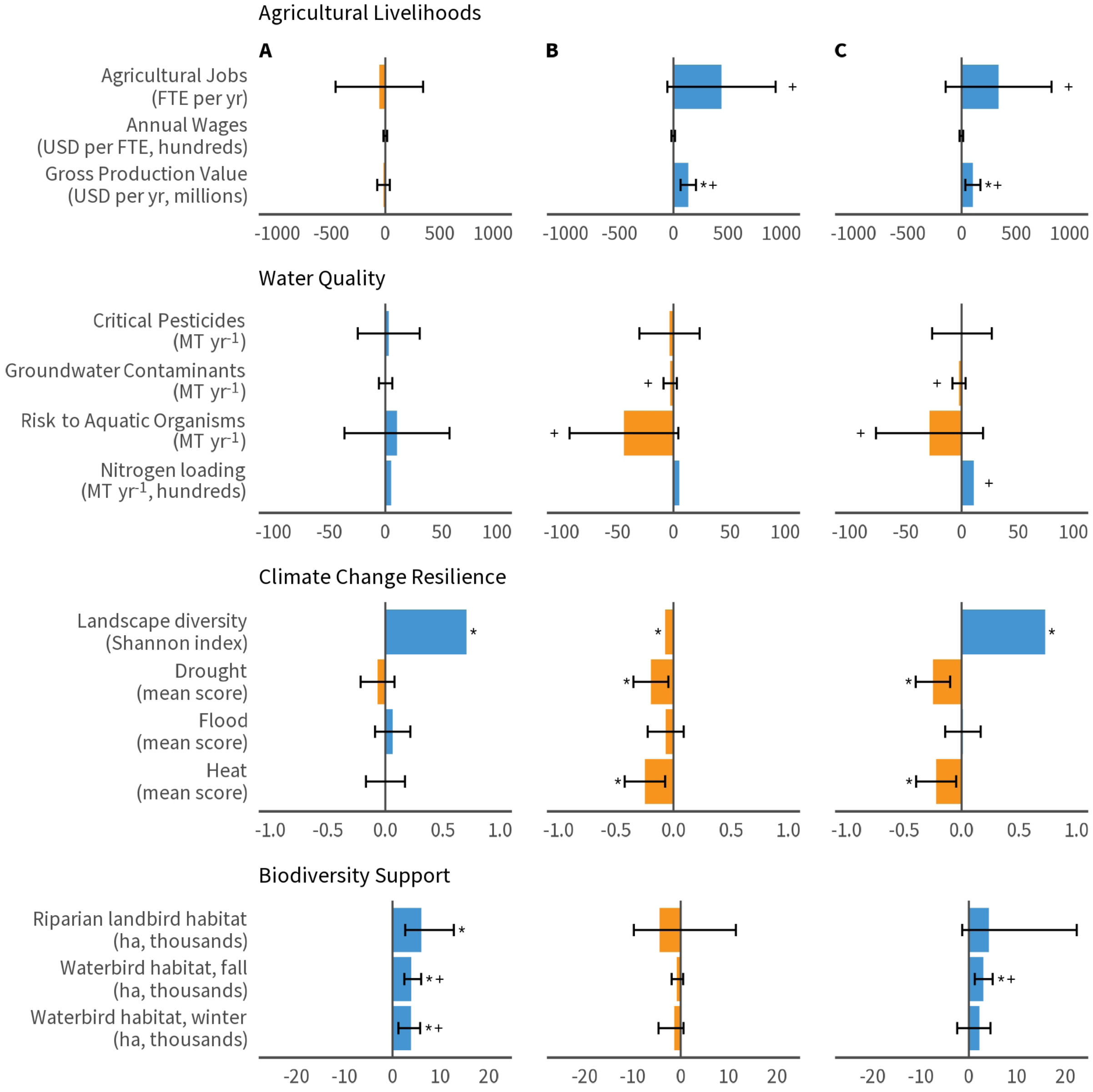

Figure 3 Net effects of each alternative landscape on multiple benefits by category. (**A**) AL1: Habitat restoration. (**B**) AL2: Perennial crop expansion. (**C**) AL3: Combination. Benefits categories include agricultural livelihoods, water quality, climate change resilience, and biodiversity support, each with multiple metrics shown in their own units. Each *bar* represents the estimated difference from baseline (d_{mL}) for each AL, with beneficial changes ($d_{mL} > 0$) shown in *blue* and trade-offs ($d_{mL} < 0$) in *orange*. Also shown is the estimated uncertainty in the difference, and whether we considered d_m to be statistically significant (∗) or practically significant (+); see "Methods" for details.

In contrast, under AL2 and AL3, we projected a mix of benefits and trade-offs relative to baseline metrics (Figure 3). Both alternatives offered agricultural livelihood benefits, including statistically and practically significant increases in gross production value per year (137.1 ± 71.3 and 104.3 ± 69.8 USD per year, millions, respectively; + 17% and + 13% from baseline), as well as practically (but not statistically) significant increases in the average number of agricultural jobs per year (444 ± 501 and 342 ± 490 FTE per year, respectively; + 18% and + 14% from baseline) (Table 2). Like AL1, both of these alternatives also offered potential water-quality benefits in terms of reduced N loading to groundwater, with a practically significant decrease of 5% projected

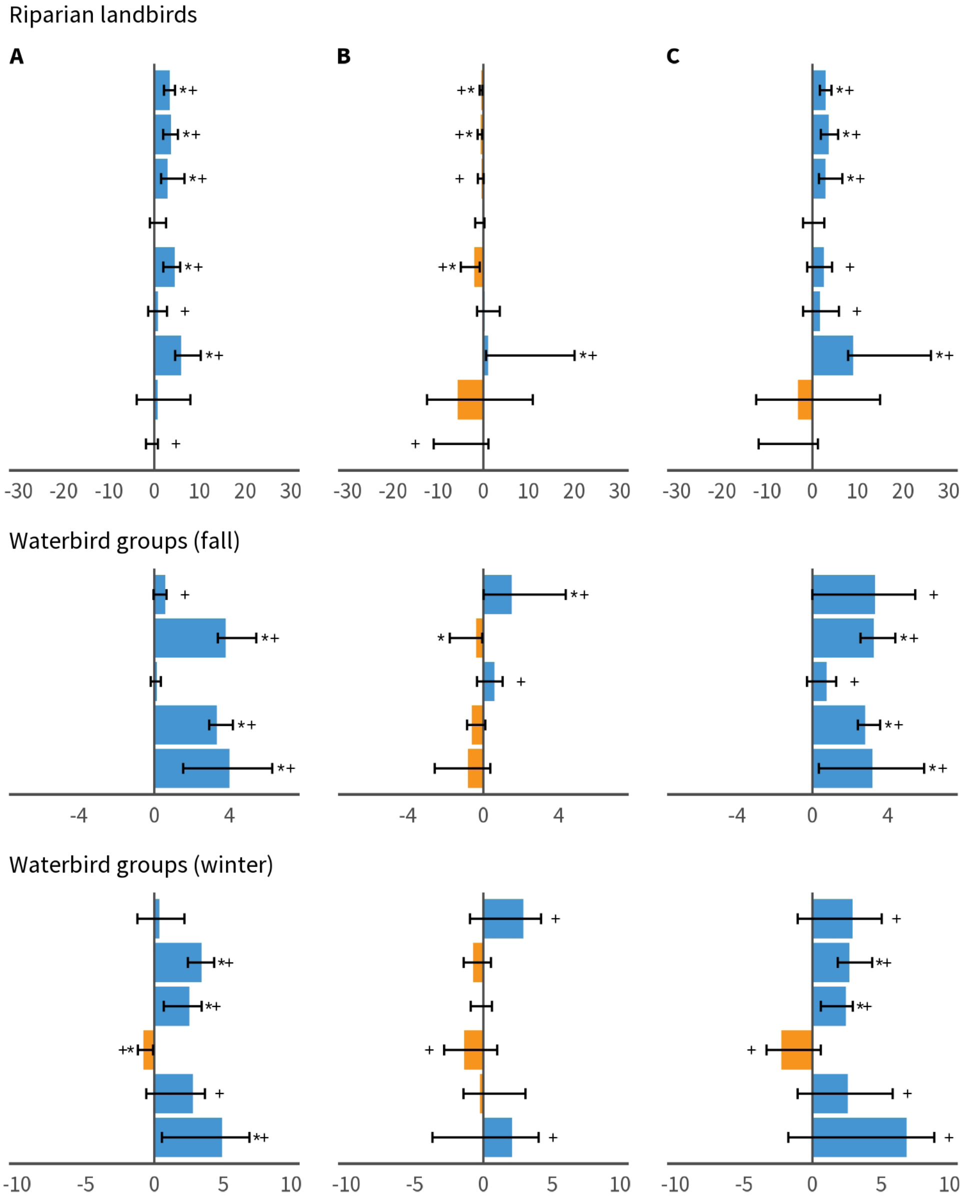

Figure 4 Net effects of each alternative landscape on individual riparian landbird species and groups of waterbird species. (**A**) AL1: Habitat restoration. (**B**) AL2: Perennial crop expansion. (**C**) AL3: Combination. Each *bar* represents the estimated difference from baseline (d_{mL}) in the total area of suitable habitat for each AL (ha, thousands), with beneficial changes ($d_{mL} > 0$) shown in *blue* and trade-offs ($d_{mL} < 0$) in *orange*. Also shown is the estimated uncertainty in the difference, and whether we considered d_{mL} to be statistically significant (*) or practically significant (+); see Methods for details.

only for AL3. In contrast to these projected benefits, we also projected significant trade-offs in other water-quality metrics and some of the climate-change resilience metrics under both alternatives. These included statistically (but not practically) significant decreases in landscape-level tolerance to both drought and heat under both, and practically (but not statistically) significant increases in the application rates of known groundwater contaminants, and chemicals known to pose a high or moderate risk to aquatic organisms.

The largest differences between AL2 and AL3 were in their landscape-diversity and biodiversity-support benefits. We found a statistically

Table 2 Landscape total scores for each metric in each benefits category, estimated for the baseline landscape and each alternative landscape. Each score is provided in its own units and, wherever possible, shown with its estimated uncertainty (see "Methods" for details).

Benefits categories and metrics	Method and units	Baseline		AL1: Habitat restoration		AL2: Perennial crop expansion		AL3: Combination	
Agricultural Livelihoods									
Agricultural jobs	Sum of FTE yr^{-1}	2,514	(144)	2,458	(142)	2,958	(205)	2,856	(198)
Mean annual wage	Weighted mean of USD FTE^{-1} yr^{-1}	38,727	(614)	38,698	(613)	38,488	(574)	38,474	(575)
Gross production value	Sum of USD (thousands) yr^{-1}	814,558	(20,702)	797,689	(20,401)	951,670	(29,015)	918,840	(28,076)
Water Quality									
Critical pesticides	Sum of MT yr^{-1}	125.43	(9.89)	122.35	(9.67)	128.96	(9.12)	125.14	(8.92)
Groundwater contaminants	Sum of MT yr^{-1}	16.24	(2.13)	15.98	(2.09)	19.18	(2.08)	18.58	(2.03)
Risk to aquatic organisms	Sum of MT yr^{-1}	392.86	(16.78)	382.44	(16.38)	437.10	(17.54)	421.55	(17.02)
Nitrogen loading	Sum of MT (hundreds) yr^{-1}	224.83		219.62		219.61		213.99	
Climate-Change Resilience									
Landscape diversity	Shannon index	2.790		2.832		2.786		2.834	
Drought	Mean qualitative index score	5.62	(0.05)	5.56	(0.05)	5.43	(0.05)	5.37	(0.05)
Flood	Mean qualitative index score	5.90	(0.05)	5.96	(0.05)	5.83	(0.06)	5.91	(0.05)
Heat	mean qualitative index score	6.94	(0.06)	6.94	(0.06)	6.69	(0.06)	6.72	(0.06)
Biodiversity Support									
Riparian landbird habitat	Model-predicted suitable ha	201,883	(3,842)	207,878	(3,624)	197,488	(3,717)	206,046	(3,447)
Waterbird habitat (fall)	Model-predicted suitable ha	25,068	(510)	28,955	(543)	24,245	(490)	28,092	(532)
Waterbird habitat (winter)	Model-predicted suitable ha	55,603	(1,650)	59,447	(1,633)	54,270	(1,489)	57,809	(1,471)

significant increase in landscape diversity for AL3 ($p < 0.001$) and a statistically significant decrease in landscape diversity for AL2 ($p = 0.02$). For biodiversity support, while we projected benefits for all three metrics under AL1, AL3 offered a significant increase in suitable habitat only for waterbirds during the fall (3,024 ha; 95% bootstrap CI: 1,233–4,959; +12% from baseline) and AL2 offered no significant benefits or trade-offs. However, for individual bird species and groups, we identified multiple statistically and/or practically significant decreases in suitable habitat under AL2, and increases only for Spotted Towhee, geese, cranes during the fall, and herons/egrets during the winter, while under AL3, there were statistically and/or practically significant increases for most species and groups (Figure 4).

DISCUSSION

Changes in the extent and spatial configuration of different land covers are likely to affect many goals and values reflected in the Delta Plan (DSC 2013). To effectively plan and implement policies and land-management decisions intended to achieve multiple goals, it is essential to quantify the potential trade-offs of a decision or action across multiple goals (Gardali et al. 2021). Our analyses provide a foundation for an open-source framework to address this information gap, by integrating multiple data sources and models, defining an initial set of metrics and benefit categories, and establishing transparent and repeatable methods for projecting their response to alternative landscapes. Our framework is designed to complement the Landscape Scenario Planning Tool (LSPT), an ArcPro Toolbox, which represented a great advance in supporting the analysis of the effects of land-cover changes on multiple metrics, largely reflecting landscape-ecology metrics (SFEI 2020, 2022). Here, we integrated additional types of data, models, and metrics in an open-source framework intended to facilitate collaborative, ongoing refinement and improvement among the Delta research community.

Consistent with previous research that demonstrated the multiple benefits associated with wetland and riparian ecosystems (Peterson et al. 2020; Conlisk et al. 2023), reaching the habitat restoration targets for riparian and non-tidal wetlands established in the Delta Plan (AL1) appeared to be a no-regrets strategy. We estimated that AL1 would provide significant biodiversity-support and climate change-resilience benefits, and possible benefits to water quality in terms of N loading. There was no evidence for benefits to other water-quality metrics, although these metrics represented only the risk to water quality from pesticide application and not the capacity of riparian areas and wetlands to filter run-off from adjacent lands and improve water quality (Duffy and Kahara 2011; Cheng et al. 2020; Gordon et al. 2020), and therefore water-quality benefits under AL1 may be underestimated. We also anticipate that the lack of evidence for benefits to other water-quality and climate change-resilience metrics, or evidence for any trade-offs to agricultural livelihoods, results, in part, from the relatively small magnitude of land-cover change in AL1 compared to AL2 or AL3 (Figure 2). Medellin et al. (2012) also described economic effects of comparable habitat-expansion scenarios as relatively low, and representing a very small share of the Delta's economy. Projected effects of habitat restoration may be more detectable when evaluated on smaller spatial scales within the Delta where a larger proportion of the landscape is affected. In addition, we note that the largest land-cover effects of AL1 were a loss of "grassland & pasture" (Figure 2), which could produce trade-offs in the total area of suitable habitat for grassland-associated species not considered here.

Unexpectedly, AL1 was projected to decrease the total area of suitable habitat for foraging Sandhill Crane, with similar projections for AL2 and AL3 (Figure 4). Our analyses included both Greater Sandhill Crane, listed as threatened under the California Endangered Species Act, and Lesser Sandhill Crane, a California Bird Species of Special Concern (Shuford and Gardali 2008). The Delta previously has been identified as important to crane conservation (Veloz et al. 2017; Dybala et al. 2020), raising concerns about these projected effects. We attributed this projected decrease in suitable foraging habitat to our assumption that existing traditional crane roosts would become unsuitable with the addition of trees, whether riparian trees or orchards. Because distance to crane roost was an important predictor of crane presence (Dybala et al. 2023), the loss of these roosts would reduce the total area of suitable foraging habitat the crane-distribution model projected under each AL. However, in identifying candidate locations for riparian restoration in AL1, which we also applied to AL3, we did not explicitly seek to avoid effects on traditional crane roosts, which could be included in criteria for actual restoration-site selection. In addition, we assumed cranes would be unable to move and establish another roost location nearby. Thus, our projections may overestimate the negative effect on cranes but suggest the need for additional attention to factors that contribute to the abandonment of roosts and establishment of new roosts.

In contrast to AL1, we found that continued expansion of perennial crops would provide significant benefits to agricultural livelihoods and possible benefits to water quality from reduced N loading but would also incur significant trade-offs. The projected increases in the total application rates of groundwater contaminants and chemicals known to pose a risk to aquatic organisms suggests that increased attention to mitigating risks to water quality would be warranted. In addition, the greater sensitivity of perennial crops to drought and heat stressors and reduction in overall landscape diversity significantly decreased the overall climate change-resilience scores. If the frequency of extreme drought and heat events increases as expected, crop yields and production may be affected (DSC 2021a), such that the benefits to agricultural livelihoods under this AL may be short-lived.

By examining the separate and combined effects of habitat restoration and perennial crop expansion, our results provide useful insights into how they interact to influence benefits and trade-offs. AL3 demonstrated that benefits to agricultural livelihoods and biodiversity support may not be fundamentally incompatible goals, although the magnitudes of the benefits were smaller than estimated under AL1 and AL2. Our decision to ensure the restoration targets were still met under AL3 resulted in a reduced expansion of perennial crops and reduced benefits to agricultural livelihoods, compared to AL2. However, even though the restoration targets were still met in AL3, the total area of suitable habitat for birds was reduced compared to AL1. Because the habitat suitability of each pixel in the landscape depends on the composition of the surrounding landscape, the biodiversity-support benefits of meeting restoration targets in the Delta Plan depend on concurrent changes in land cover and agricultural practices, and thus the results of AL3 for biodiversity support are not a simple sum of AL1 and AL2. In this case, AL3 demonstrated that an expanded footprint of perennial crops could reduce the effectiveness of the same magnitude of restoration effort. Thus, land-management or policy decisions aimed at enhancing benefits to agricultural livelihoods, biodiversity support, or both require careful consideration of the interactions between these drivers of landscape change. For example, restoration targets in the Delta could be increased to offset the effect of nearby perennial crop expansion and ensure sufficient biodiversity-support benefits; incentives not to convert to perennial crops could be provided where they would contribute most to biodiversity-support benefits; and/or the location of restoration efforts could be selected to avoid areas most likely to convert to perennial crops. Restoration adjacent to existing priority bird-conservation areas may be particularly strategic in creating protective buffer zones, increasing the size of suitable habitat patches, and reducing fragmentation to maximize benefits to birds (Marzluff and Ewing 2001; Barbaree et al. 2018; Dybala et al. 2023).

FUTURE DEVELOPMENT AND APPLICATIONS

In this analysis, we considered three alternative landscapes to explore the effects of two major drivers of landscape change in the Delta, providing important insights into their interaction and applications to regional restoration targets, land-management strategies, and policy. Our general framework provides a foundation for extending these analyses to examine new or revised ALs. For example, our restoration AL could be revised as additional restoration projects are developed, and the perennial crop expansion AL can be refined to incorporate more detailed, local information about the probability of crop conversions, considering factors such as soil properties, water supply, or costs of conversion. Alternate versions of the restoration AL could also be developed to explore the sensitivity of the results to different spatial configurations of the potential future restoration projects, such as the effects on each benefit category of prioritizing non-tidal wetland restoration in the central Delta instead of in the Priority Habitat Restoration Areas. New ALs could be developed to evaluate benefits and trade-offs of individual proposed projects, such as plans to transform entire islands (MWD 2023). More complex future landscape scenarios could also be developed and analyzed to represent the effects of other drivers of landscape change not yet considered here (e.g., sea level rise, subsidence, and changing flood risk, as well as increases in tidal wetlands, subsidence reversal wetlands, and rice farming).

The benefit categories and metrics we examined are not comprehensive of all goals or values for the Delta. We encourage and welcome collaborative efforts across disciplines to identify and incorporate additional metrics, data sources, and models into our open-source framework to provide more comprehensive and refined estimates of the benefits and trade-offs of the evolving Delta landscape. For example, distribution models or habitat-suitability criteria developed for other flora and fauna of interest could be incorporated to expand biodiversity-support metrics, and existing metrics for agricultural livelihoods or water quality could be refined by incorporating additional years of source data or by developing spatially explicit models that can more accurately predict the variation in each metric within the Delta. In addition, new metrics could be developed from data and models that represent rates of land subsidence or subsidence reversal (Windham–Myers et al. 2023), recreational opportunities (Mickel et al. 2019), applied water use (CDWR 2022), greenhouse gas emissions (SFEI 2022), or jobs, wages, and economic value related to tourism, hunting, habitat restoration, and the management of wetlands and other natural land covers in the Delta, among others. Metrics could also be selected to represent or complement the Delta performance measures (DSC 2022b). Variation in land management within land-cover classes—such as decisions to flood agricultural fields post-harvest to provide habitat for migrating and wintering birds, or safety measures implemented to protect water quality from pesticide applications—can also be important drivers of variation in these benefits; an ability to represent the response of these metrics to land management would allow for the evaluation of proposed or anticipated changes in land management to be incorporated into evaluations of ALs.

The primary challenges with developing any new ALs or metrics—or refining metrics to incorporate land-management detail—lies in ensuring each land-cover class under consideration can be assigned a value for each metric of interest under each AL and set of management conditions. Here, for example, we excluded tidal wetland restoration from consideration in these analyses, given a lack of comparable data to support estimating the anticipated benefits to bird habitat from tidal wetland restoration as we did for riparian and non-tidal wetland restoration; we are currently working toward extending this framework to analyze an AL that represents tidal marsh restoration by incorporating Suisun Marsh and new data that will allow us to estimate benefits to tidal marsh birds. Future analyses using this framework should carefully consider the data available to represent the benefits metrics of interest in the context of the primary land-cover changes that will occur under any alternate landscape to be analyzed. In addition, because of the sensitive nature of mapping landscape changes that could deeply affect local communities and their livelihoods—especially changes to private lands—we recommend careful communication that clearly distinguishes any ALs developed solely for exploring the potential effects of landscape change, as in this analysis, from actual proposals of landscape change.

CONCLUSIONS

Our results demonstrate the potential for landscape changes to result in a complex array of benefits and trade-offs and the strengths of integrating multiple datasets across science disciplines to quantify the effects of landscape change. Our framework provides a flexible, open-source foundation for further development and collaboration among scientists, managers, policy-makers, and other interested parties to: (1) include an increasingly comprehensive and diverse array of goals, values, and metrics as they are identified by managers, planners, and local communities; (2) integrate more data and models among Delta scientists and disciplines to be able to evaluate each metric; and (3) facilitate communication and understanding of the effects of proposed or anticipated landscape changes. Such representation, integration, and understanding are essential to identify and address trade-offs, inform policy and management decisions, and, ultimately, support the practice of Multiple-Benefit Conservation in the Sacramento–San Joaquin River Delta.

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DATA AVAILABILITY STATEMENT

The 'DeltaMultipleBenefits' R package is available from GitHub (*https://pointblue.github.io/DeltaMultipleBenefits*) and Zenodo (*https://doi.org/10.5281/zenodo.7718620*).

The baseline and projected future land-use and land-cover data (shown in Figure 1) are available from the California Department of Fish and Wildlife Biogeographic Information and Observation System (BIOS) *https://apps.wildlife.ca.gov/bios6/?bookmark=356*

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