Nature-based Solutions to Reduce Carbon Emissions, Control Groundwater Overdraft, and Conserve Avian Biodiversity with Multi-Benefit Conservation Planning

Abstract

Climate change is projected to alter biodiversity conservation's spatial and temporal cost-effectiveness. Species' migratory and phenological adaptations shape climate-driven shifts in range and abundance, and the opportunity costs of conservation—particularly land and water—are expected to increase with more frequent extreme temperature and hydrological events. We developed an integrated framework that combines species distribution models to estimate biodiversity metrics with economic models to quantify conservation opportunity costs under climate change. This integrated approach supports spatially and temporally explicit systematic conservation planning. We applied the framework to California's Central Valley, modeling weekly distributions of 15 shorebird species and evaluating land and water opportunity costs under historical and climate change scenarios. Conservation actions focused on the creation of dynamic flooded habitats on agricultural lands—a nature-based solution to support carbon sequestration, groundwater recharge, and avian biodiversity simultaneously. Results highlight the importance of aligning conservation with timed agricultural land use across seasons. When trade-offs in water and land use were considered, prioritization favored non-productive seasons to sustain agricultural viability. In contrast, ignoring economic trade-offs led to prioritizing the land with the highest biodiversity value. Our findings indicate that dynamic habitat conservation is ten times more cost-effective than static habitat approaches. Climate change scenarios also yielded higher spatial connectivity requirements in conservation planning while achieving equivalent levels of biodiversity protection, water conservation, and carbon sequestration. These results underscore the value of climate-smart, flexible conservation strategies for effective adaptation.

Keywords: Nature-based Solutions, Conservation Planning, Carbon Sequestration, Groundwater Recharge, Dynamic Habitat

1. Introduction

Biodiversity is threatened by climate change (Gerling et al., 2022). Intermediate conservation actions are required to limit the potential extinction of millions of species exacerbated by climate change (Wiens & Zelinka, 2024). The United Nations declared that nature-based solutions to carbon sequestration, water challenges, and ecosystem health pose a solution to overcome 21st-century global challenges. Nature-based solutions are to reinforce natural processes and utilize "green" infrastructure (e.g., wetlands, floodplains, aquifers) (European Commission, Directorate-General for Research and Innovation, 2015) as a means to efficiently address multiple people-nature challenges, such as droughts, floods, greenhouse effects, and human-caused species extinction. Simultaneously, climate change metrics are integrated into drawing the plan (Buenafe et al., 2023) for climate-smart conservation planning.

Climate change will alter species' spatial and temporal distribution and reshuffle community compositions. Implementing climate-smart conservation with nature-based solutions for multi-benefit objectives requires systematic evaluation of the benefits from conservation choices and managing trade-offs between benefits (Nesshöver et al., 2017). The benefits of mitigating climate change, water management, and biodiversity conservation, if unaligned or even at odds with each other, can be costly and highly problematic. Systematic conservation planning (SCP) (Margules & Pressey, 2000) that simultaneously addresses these challenges with a future-oriented approach is needed to avoid unintended consequences of habitat disconnection, aquatic biodiversity losses, and decreased agricultural income because of unaligned management objectives. Therefore, SCPs require knowledge of not only the high biodiversity level for both the present and future but also what opportunities co-exist so as to leverage biodiversity simultaneously with other ecosystem service opportunities (Sievers et al., 2023). California's managed wetlands support the highest densities of wintering waterfowl found anywhere in the world (Petrie & Petrik, 2010). California's groundwater resources have been over-drafted for a century (Faunt & Geological Survey (U.S.), 2009), with most of the critically over-drafted basins in the Central Valley (DWR 2016). Additionally, Groundwater is an important resource for compensating for water shortages during droughts (Howitt et al., 2014). Wetlands not only create green infrastructure to store groundwater but also store blue carbon with capacity increasing with climate change (Wang et al., 2021).

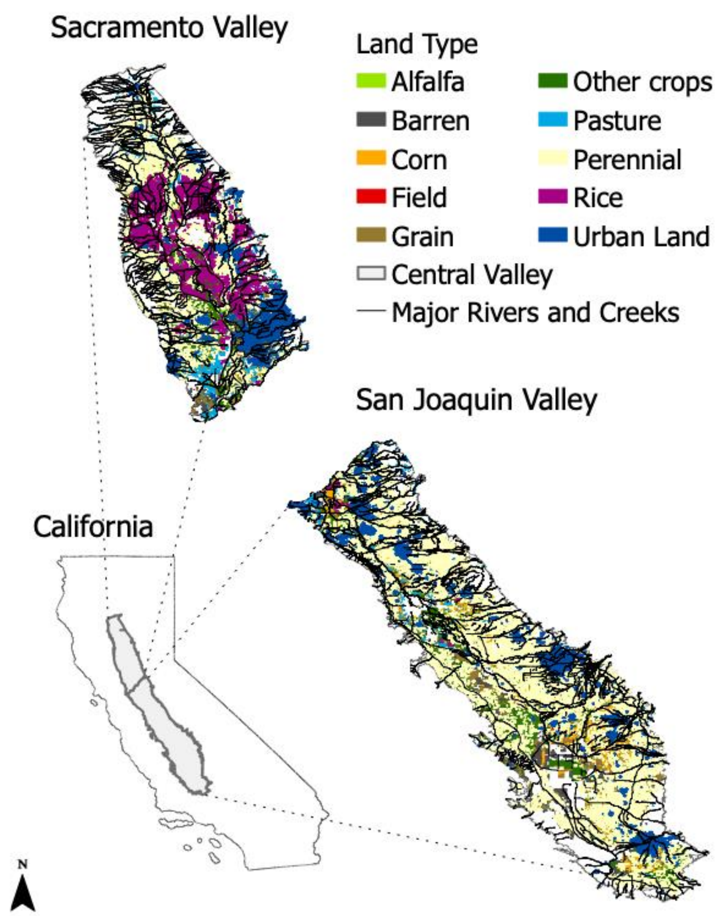

Figure 1. Regional map of the Central Valley, California, with the Sacramento Valley and San Joaquin Valley comprising the whole Central Valley (gray polygon), occupying the Central part of California.

The practice of renting or temporarily utilizing appropriated agricultural land and water to offer birds habitat for the full annual migratory circle and across California's Central Valley (Figure 1) is called a "pop-up" habitat. The pop-up habitat was introduced by the Nature Conservancy's BirdReturns Program to compensate farmers for the costs of applying water to their fields to a suitable depth for migratory shorebirds. Previous research (Rohde et al., 2020)has already established a series of "pop-up" habitats in Central Valley based on a suite of targeted species abundance (Sullivan et al., 2009) and water availability estimated based on NASA Landsat imagery (Reiter et al., 2015). While providing habitat benefits, BirdReturns replenished groundwater aquifers (Matsumoto et al., 2019). However, groundwater recharge based on water availability only, without considering recharge suitability, may potentially cause groundwater aquifer contamination by recharging on some agricultural lands that have been fertilized.

It has been shown that dynamic habitats like the variable drawdown on flooded rice fields successfully extend the availability of waterbird habitat, compensating for the shallow water habitat loss elsewhere (Sesser et al., 2018). Past research has studied bioenergy, the length of staggered drawdown periods (Sesser et al., 2018), socio-economic frameworks (Rohde et al., 2020; Serra-Llobet et al., 2022), the association of the tidal cycle and habitat type with habitat choice (Long & Ralph, 2001), and water-saving treatment options for flooding (Strum et al., 2013) source Conlisk et al., (2022) used abundance-weighted boosted regression trees and modeled monthly shorebird occurrence as a function of surface water availability, crop type, wetland type, road density, temperature, and bird data.

However, these existing dynamic habitat studies were temporally constrained to 2- to 8-week periods during critical spring and fall migration and mainly focused on utilizing fallowed and harvested rice lands in the northern half of the Central Valley-Sacramento Valley (Sesser et al., 2018)(Golet et al., 2018). The favorable field characteristics vary among shorebirds with different foraging behavior (Long & Ralph, 2001; Reynolds et al., 2018). Focusing on the rice lands and limiting the flood periods will restrict the conservation benefits and neglect other key stages of the annual migration cycle. In addition, climate-driven shifts in the geography of life drive changes in conservation prioritization (Moradi et al., 2019). Conservation objectives accounting for climate change impacts should acknowledge that species will move beyond their traditional ranges to avoid investing in protecting species in locations where they are no longer viable and yet failing to manage them appropriately in their new ranges (Pecl et al., 2017). Considering the increased cost of conservation resources, seasonal abundance-adjusted targets are more helpful in elevating the prioritization of seasonally abundant migratory species than static targets (Haupt et al., 2017).

With these considerations, instead of only seeking appropriate habitat on rice lands, this research extended to broader crop categories, searching for appropriate farmlands for dynamic habitat recreation across all seasons. Our conservation planning also resonates with the agricultural land repurposing planning in the southern half of the Central Valley-San Joaquin Valley. In our work, we developed a spatial and temporal systematic conservation planning framework that can assist in locating "pop-up" habitat that meets the multiple objectives of high shorebird conservation values, high groundwater recharge suitability, and carbon sequestration capacity building to combat climate change impacts. It is essential to make validated species range predictions and select suitable sites that match the needs of the focal species under both current and future climates (Jarvie & Svenning, 2018). Therefore, we generated a pop-up habitat prioritization based on birds' abundance predicted under historical and climate change scenarios. This prioritization strategy can guide actionable conservation and water allocation in California. Almost 90% of California's original wetland habitat has been transformed into farmland over the past century. The remaining wetlands are mostly disconnected from the natural water system for water network simplification, relying on local water allocation decisions for wetland habitat water supply. Thus, water rights and policies dictate wetland water application more than natural factors (Grantham & Viers, 2014).

Here, we use systematic conservation planning (SCP) informed by species distribution models and economic optimization models to perform spatial and temporal explicit conservation planning in the Central Valley, California. Both conservation features, particularly biodiversity features, and conservation costs varied across seasons to drive the seasonally dynamic and spatially explicit configuration of dynamic habitats. Spatial and temporal explicit SCP (STE-SCP) was implemented for biodiversity conservation, groundwater recharge, and carbon sequestration potential co-optimization. Historical and climate change prioritizations were modeled for the flooded habitat conservation approach to inform climate-smart conservation areas. We pictured how climate change would affect the spatial configuration of habitat prioritization using Cohen's Kappa coefficient and K-means cluster analysis of Jaccard distances of conservation solutions with different climate change scenarios. Considering the increasing cost of climate change, a temporal and spatial conjunctive prioritization was used to seek the optimized timing and locations for such dynamic habitats to inform cost-effective conservation resource use.

2. Method

2.1. Avian biodiversity conservation objectives

Climate change will shift migratory species' spatial and temporal distribution due to migratory and phenological adaptation (Harris et al., 2018). Species distribution models (SDMs) are widely used to derive species range predictions and support robust conservation management (Guisan et al., 2013). They are increasingly used to analyze how climate change and land use changes may alter range extents or cause distributional shifts (Brodie et al., 2020).

Additionally, accounting for species' response to climate change has magnified the uncertainties and challenges of achieving effective conservation, as climate change will reassemble the species community with various strengths and directions of environment-species interactions. SCP studies can synthesize SDM outcomes of multiple species to generate the spatial representation of conservation reserves that maximize the habitat unities for a species' community composition. We picked an ensemble of shorebird species listed in the report dictating shorebirds of Conservation Concerns(USCPP, 2015). We tried to exhaust all the shorebirds listed except those not present in Central Valley and those evenly distributed across Central Valley with very high abundance and least concern. The shortlisted 15 species cover a range of morphological features (particularly size varieties), prevalence, and conservation status to represent a broad range of shorebird species in the Central Valley.

We used an ensemble species distribution model--spatiotemporal exploratory model (STEM) (Fink et al., 2010) to generate estimates of weekly relative abundance for each species. STEM was well described in (Johnston et al., 2015). We followed the setup in Li et al., (2025a) to divide the Central Valley into randomly located (5° × 5° × 30 continuous days) Monte Carlo spatial-temporal blocks. Multiple blocks overlap at a given location and give estimates using Boosted Regression Models as block models. The prediction outcome is the average estimate at a location and dates of all the local models (100 blocks). The spatial-temporal partition of training data is similar to partial pooling in Bayesian statistics, which controls overfitting and overgeneralizing species-environment relations (de Rivera et al., 2019).

2.2.Groundwater recharge and carbon sequestration objectives

A future-oriented approach to biodiversity conservation should consider threats and opportunities posed by climate change adaptation strategies. Although reserves accounting for climate change might increase the conservation cost with the extended protected areas (Lawler et al., 2020), such cost can be potentially compensated by increased biological value brought by the refugia (Strassburg et al., 2020), carbon credits, or groundwater renewal benefits.

Wetlands are carbon sinks, and their global average carbon sequestration rate is 0.58 tC $ha^{-1}yr^{-1}$(Li et al., 2023). Comparatively, the carbon sequestration capacity on agricultural lands is minimal (0.05 tCha-1yr-1 (Cao et al., 2023; Liu et al., 2011). Therefore, we assume flooded land has the same carbon sequestration capacity as wetlands, providing a carbon sequestration ecosystem service. If a planning unit is selected, the farmlands in the planning unit will be flooded to create habitats and capture 0.58 tC $ha^{-1}yr^{-1}$ carbon.

We used groundwater recharge suitability as a groundwater recharge feature. Recharge suitability is represented by the Soil Agricultural Groundwater Banking Index (SAGBI) (O'Geen et al., 2015). SAGBI represents suitable soil condition areas and scores higher for agricultural land parcels planted with pasture, vineyards (perennials), rice, and alfalfa. Vineyards and pastures are particularly suitable for groundwater recharge, as no or only minimal nitrogen fertilizer is needed. Hereby, the risk of groundwater contamination from recharge is very low on these lands.

2.3.Conservation cost considerations

The quantity and quality of distribution data, cost layers, and threat data must be interpreted to understand the conservation prioritization results for climate change adaptation. Many efforts have been made to collect and improve distribution data and data-generating models. However, cost and threat data layers may influence the conservation results at a higher order than distribution data (Kujala et al., 2018). For example, the influence of a single cost layer can even be as significant as the joint influence of thousands of species distributions in a classical cost-effectiveness B/C formulation (benefits divided by costs).

Planning unit costs comprise land costs and conservation action costs. The land cost is approximated by calculating the net returns for the foregone annual agricultural production. Crop unit net returns of each crop category were acquired for the most recent year, Sacramento Valley survey from UC Davis Agricultural& Resources Economics Cost & Return Studies. (https://coststudies.ucdavis.edu/current/commodities) . The net return above operational cost was used, assuming the costs, such as infrastructure and equipment, were already incurred, regardless of the conservation status. The conservation action cost is approximated as the water cost for flooded habitats. Water economic cost is calculated from the hydro-economic optimization model CALVIN (Draper et al., 2003). The water economic cost is the Lagrange multiplier on the water storage constraints, representing the cost of releasing an additional water unit from reservoirs. Water volume is based on the optimal water depth for shorebirds, which is 10cm (Strum et al., 2013), multiplied by the flooded areas of the planning unit. The flooding pulse is every other month, a one-time flooding without maintenance for the 2 months. We also calculated the water transfer costs from the reservoir to the refuge or flooded location by multiplying the unit transfer cost ($ 1000 $m^{-1}kaf^{-1}$) by the distance between the focal location and the water source.

2.4.Environmental change scenarios for future-oriented conservation

We embedded climatic condition changes into land cover changes to facilitate future-oriented conservation planning that can still be effective with environmental changes. Bird abundance modeling and carbon sequestration calculation rely on land cover changes and, therefore, are dynamic with climate change. The groundwater recharge feature is static with climate change because recharge suitability is not dependent on land use classes only. Recharge suitability also differs with varying historical geological conditions. Both land use and soil conditions were integrated into SAGBI.

We followed an economic water and land allocation optimization approach Li et al. (2025b) used for land cover projection with climate change. The historical scenario is derived from 1950 to 1999 hydrology, and climate change scenarios were projected for 2050-2099 hydrology. An agricultural land use proportional change was derived from the Positive Mathematical Programming (PMP) land use optimization model described in (Howitt et al., 2012) to construct climate change land cover. Agricultural land use change was driven by water availability change due to climate change. The water allocation optimization model, CALVIN (Draper et al., 2003) was used to generate different water availabilities for agricultural water use. The hydrological variables for creating historical and climate change scenarios are surface water runoffs and precipitation, acquired from the VIC Model Output of Daily Runoff for 1/8th Degree (Hamman et al., 2018), and the Multivariate Adaptive Constructed Analogs (MACA), respectively (Abatzoglou & Brown, 2012). As our climate future is uncertain (Harris et al., 2014), we used two climate models participating in the Fifth Coupled Intermodel Comparison (HadGEM2 and MIROC5) that were statistically downscaled to present a range of California's future climates. Climate model selection was based on the shortlisted climate models deemed suitable for California's hydroclimate (Pierce et al., 2018) and restricted by the water optimization model CALVIN's capacity to handle extreme inflows projected by non-selected climate models.

We used Cohen's Kappa Coefficient (McHugh, 2012) to quantify how climate change modifies the prioritization areas by comparing the degree of agreement between selected habitats with different climate scenarios. A Kappa of 1 indicates that solutions are the same, and zero indicates that solutions are very different. We compared 30 solutions for each climate change scenario when conservation targets are 20% and 25%, respectively, with target gaps within 20%.

2.5. Conservation prioritization with maximized benefit and minimum cost

We applied both minimum set and maximum features SCP problems to implement two different decision-making scenarios, minimizing land and water cost required for meeting targeted conservation and maximizing conservation effectiveness with a conservation investment budget, respectively. All SCP problems were implemented in the prioritizR package (Hanson et al., 2019) with mixed integer linear programming (MILP) solved in the Gurobi algorithms solver (Gurobi Optimization, 2020). All the problem code was written in the R programming language (R Core Team, 2021). PrioritizR has an identical function to Marxan with zones (Ball et al., 2009) when using the minimum set objective function (Rodrigues et al., 2000). That is to find the set of planning units that minimizes the overall cost of a reserve network while meeting a set of representation targets defined for each of the conservation features. The difference between prioritizR minimum set and the Marxan is that the targets for the features do not use Species Penalty Factors and will always be met if the target gap is zero (Hanson et al., 2019). The flexibility in prioritizR interface for building and solving SCPs allowed us to conveniently perform multiple types of SCP problems.

We compared flooded habitats utilizing non-production and full-year agricultural land to compare the costs of dynamic and static (intact) habitats. We prioritized habitat selection and incorporated human-developed landscapes in a fashion of over per week per species in a full-year cycle. This dynamic habitat approach can potentially better delineate conservation priority and improve conservation efficiency dramatically compared to the intact habitat approach (Schuster et al., 2019).

2.6.Spatial and temporal conservation planning for cost sharing

Considering the increased cost of conservation resources, seasonal abundance-adjusted targets were useful to elevate the prioritization of seasonally abundant migratory species (Haupt et al., 2017). Spatial and temporal conservation planning has attracted research attention for climate change drives species changes and seasonal changes of volant species(Dupont-Doaré & Alagador, 2021; Haupt et al., 2017). Haupt compared the conservation areas selected with and without seasonally adjusted dynamic targets and found that static conservation area designs require larger and more expensive areas to meet the same conservation targets that dynamically prioritized areas. Ignoring the seasonal fluctuation of species abundance may result in unmet targets, particularly for vulnerable migratory species. Makino et al. (2014) used spatial and temporal Conservation planning and identified the coral conservation areas that are going to be persistently functional and that are not with climate change. The conservation system costs increased by 14% with consideration of coral range shifts (Makino et al., 2014).

The temporal resolution of conservation features can impact prioritization by implicating both species' distinct migratory patterns (Johnston et al., 2020) and adaptation trajectories (Haupt et al., 2017). Fine-resolution temporal data can elevate effectiveness in the design of climate-smart protected area networks by convoluting species' adaptive trajectories (Haupt et al., 2017). For migratory species like shorebirds, seasonal dynamics necessitate even finer data, such as weekly and monthly ranges, for conservation guidance. (Johnston et al., 2020) found weekly abundances are more appropriate than range data and weekly or annual resolution for migratory species conservation planning. Therefore, we use weekly shorebird abundance derived from species distribution models as biodiversity conservation features. Multi-zone SCPs in prioritizR package has the identical optimization functions to Marxan with zones (Ball et al., 2009) when using the minimum set objective function (Rodrigues et al., 2000).

Minimize:

$$\sum_{i=1}^{m}\sum_{k=1}^{p} c_{ij}x_{ik} + b\sum_{i1=1}^{m}\sum_{i2=1}^{m}\sum_{k1=1}^{p}\sum_{k2=1}^{p} cv_{i1,i2,k1,k2}x_{i1,k1}\,x_{i2,k2} \qquad \text{Equation 1}$$

Subject to:

$$\sum_{i=1}^{m}\sum_{k=1}^{p} a_{ij}\,a_{jk}x_{ij} \geq t1_j\forall \qquad \text{Equation 2}$$

where m is the number of planning units and p is the number of zones. We used zones to represent each of the 12 months from January to December. The first term of Equation 1 represents the sum of the costs for a configuration of planning units where each planning unit i is allocated to a particular month k and is composed of a control variable $x_{ik} \in \{0,1\}$ and a cost matrix. Each planning unit can only be allocated to one zone ($\sum_{\mathrm{k}=1}^{\mathrm{p}} \mathrm{x}_{\mathrm{ik}} = 1\forall\mathrm{i}$). Hence, the month (zone) selected in the solution represents that a particular unit contributes the most to conservation if flooded during the selected month. The cost matrix $\mathrm{c}_{\mathrm{ij}}$is the cost of placing each planning unit i in zone k (see conservation cost section for how we define monthly varying costs) The second term of

Equation 1 is composed of a connectivity matrix recording the cost of the connections between planning units $i1$ and $i2$ if and only if $i1$ is in zone $k1$ and $i2$ is in zone $k2$. We implement connectivity cost by adding both spatial and temporal penalties.

Previous studies have focused on spatial connectivity and overlooked the temporal component required for the functionality of spatial connections (because of temporal changes in water availability) (Hermoso, Ward, et al., 2012). Regions like California embrace very clear wet–dry seasonal climates, and connectivity is constrained by the presence of water. Flooding in consecutive months can increase the water residence time (Hermoso, Kennard, et al., 2012), producing prolonged habitat functional time. Therefore, we applied a disconnection penalty for two consecutive months (Supplementary Information Figure 1).

In Equation 2, a_{ij} is a feature matrix that records the amount of each feature j in each planning unit i; the parameter $t1_j$ is a representation target for each feature, j, that records the amount of each feature required to be included in the zone configuration. The term a_{jk} is a contribution matrix that records the level of protection if planning for a multi-zone protected area offered to each feature j by each zone k. The feature matrix was defined by species abundance, groundwater recharge suitability, and the flooded areas' carbon storage increase by converting farmlands to wetlands over the month period.

The contribution matrix is set to 100%, which means if a unit is selected, all features in the unit are protected, although only half of the farmlands will be flooded. The proportion of flooded farmlands was determined based on previous studies on birds' preferences for combined flooded and unflooded habitats (Elphick, 2000). Birds such as killdeer and long-billed curlew spend their time feeding, sleeping, and preening with equal proportions on flooded and unflooded farmlands. Birds were observed in about 36% of flooded habitats.(Jurkiewicz-Karnkowska, 2011). The planning units in the Central Valley have a mean cropland coverage of 72% (Supplementary Information Figure 2). Therefore, we decided on 50% flooded farmlands for each selected unit to conserve 100% of the features.

2.7.Trade-off analysis for different conservation objectives

An extension of conservation planning is supporting decision frameworks that balance trade-offs that may arise between conservation and other outcomes (Manhães et al., 2018). Trade-offs exist between establishing conservation reserves and agricultural production for competing land use resources while considering conservation planning, siting, and associated restoration benefits (Finn et al., 2023). We conducted two sets of trade-off analyses using a hierarchical approach. One set was for the trade-off analysis of the cost budget and cumulative percentage of restoration, and another was for conservation targets, and costs followed (Hanson et al., 2019). Specifically, we defined varying budgets and targets and generated candidate prioritizations.

Connectivity (boundary length) penalties were also determined using trade-off analysis between conservation cost and conservation metrics with a blended approach. That is defining varying penalties, running prioritization with each penalty, and comparing each penalty point's cost and boundary length. Optimized trade-offs between cost and boundary lengths were found among the outcomes of three decision-support tools using a combination of TOPSIS (Tzeng & Huang, 2011) and Cohon (Cohon et al., 1979) methods. Penalty values are proportional to the planning unit cost term in the prioritization at monthly and annual cycle temporal scales. The planning unit costs vary across the year. The static full-year prioritization has a 10 times bigger penalty than the monthly dynamic habitat selection (the monthly cost is lower). The preferred boundary length can also determine the penalty values (Supplementary Information Figure 3).

3. Results and Discussion

3.1. Unmet conservation objectives

Conservation on California's land is conducted by ownership or easement, specifically the California Protected Areas Database (CPAD) (CRNA, 2023) and the California Conservation Easement Database (CCED) (CNRA, 2023). We compared CPAD (Figure 2a) and CCED (Figure 2b) covered areas with the spatial configuration of selected conservation prioritization areas with 30% conservation targets (Figure 2c). CPAD and CCED have more areas covered in the Sacramento Valley than in the San Joaquin Valley. Most of the prioritized planning units have less than 30% coverage by CPAD and CCED (Figures 2d and 2e).

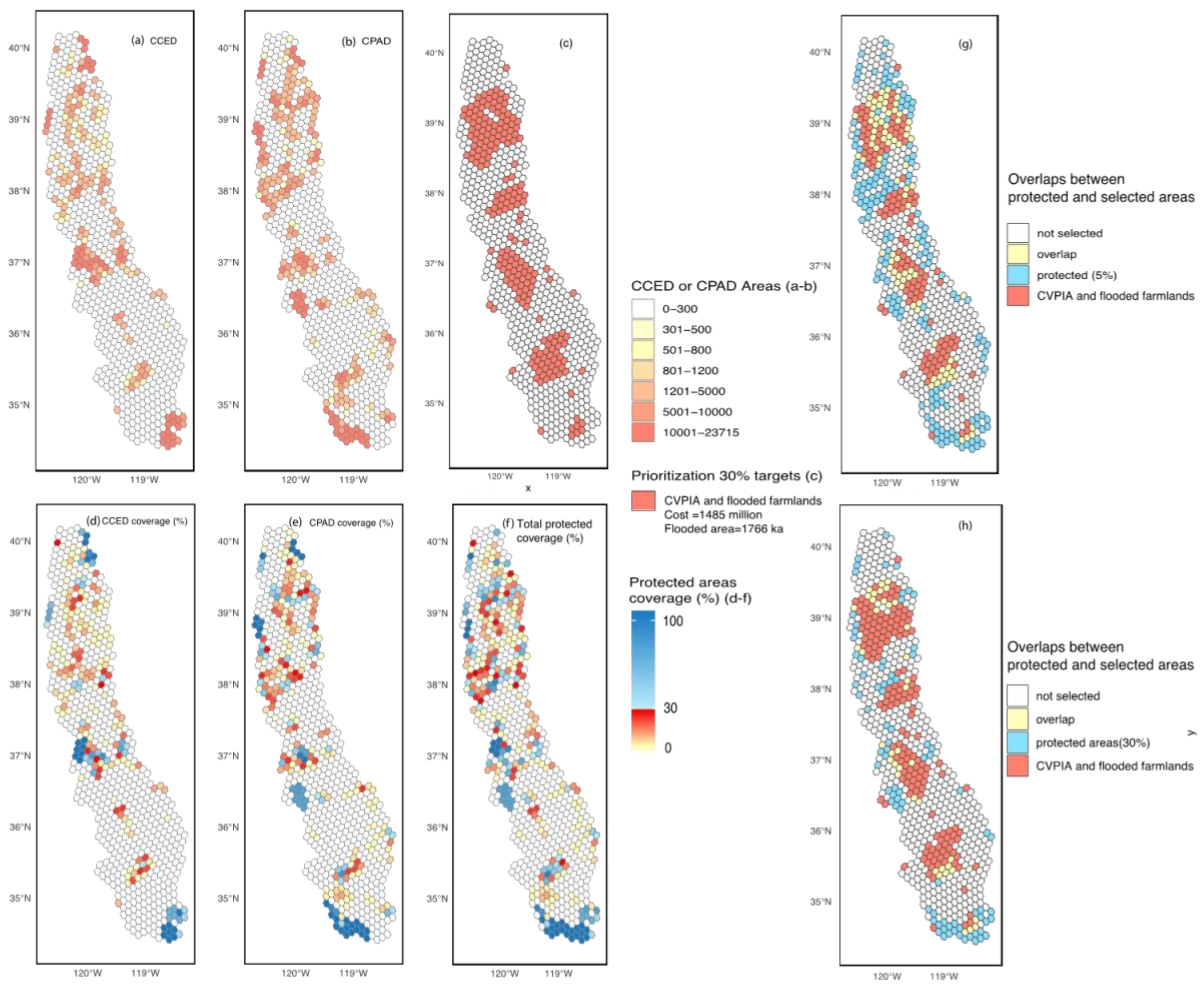

Figure 2. Coverages of CCED and CPAD in planning units in acres (a-b) and percentage (c-e), and overlaps between the selected prioritized planning units with protected planning units with coverage (f) over 5% (at least 5% of each planning unit is covered by CCED or CPAD) and (g) over 30% (at least 30% of each planning unit is covered by CCED or CPAD)

Figure 2f reported how many planning units selected by prioritization overlapped with planning units, with at least 5% protected by either CPAD or CCED. Figure 2g shows that only half the overlapping units remain when we increase the CPAD- and CCED-protected coverage threshold to 30%. The difference between Figure 2f and Figure 6g showed where the unmet 30% coverage can be improved near the publicly protected areas. Additionally, the planning units in orange in Figure 2h showed the areas where dynamic flooded habitats should be prioritized as they have significant values in achieving 30 by 30 targets (conserve 30% of the Earth's land and water by 2030 - a key component of the Kunming-Montreal Global Biodiversity Framework) (UNEP, 2022), which are not covered by any of the current static conservation approaches.

We reported how well the protected and selected planning units represent and provide protection to all three categories of conservation features by comparing the feature coverage achieved in them (Figure 3). When planning units with over 5% protected area coverage were considered, although there are 40% more planning units than selected habitat, the selected habitat has bigger average feature representations (Figure 3a). 5% coverage is not enough to meet the conservation requirement by flooding 30% of the land for habitat provisioning; thus, even when the protected areas overlap with selected habitats, they have unmet targets in some of the protected, underrepresented regions. When considering lands with over 30% protected areas coverage, the protected areas had very low feature representation from 5%-30% per planning unit. The overlapped areas have less than 20% feature coverage at most, based on the selection frequency.

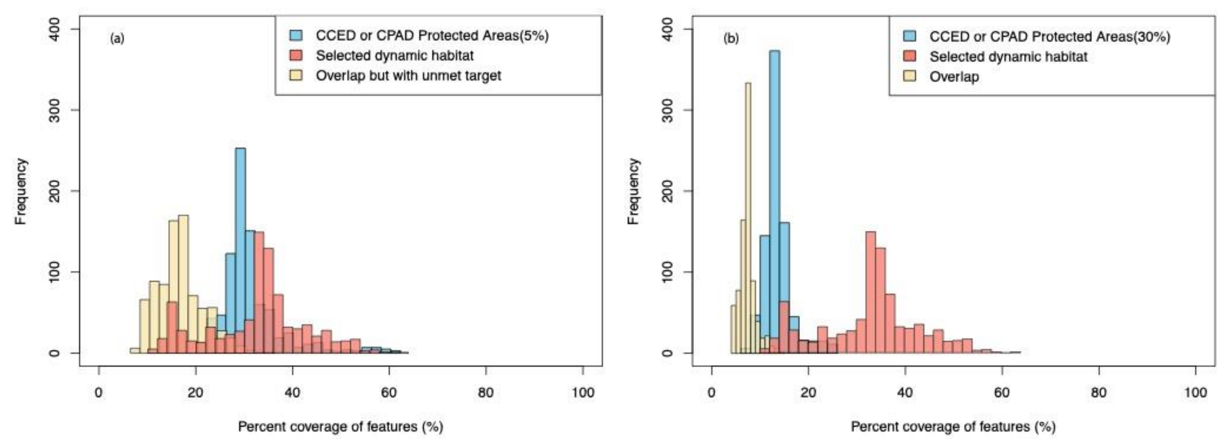

Figure 3. Percent protection of all features across selection frequencies in the spatial prioritization in this research (Salmon colored), CCED- and CPAD-protected (Skyblue colored), and their overlapping (Pale yellow colored) planning units (a) at least 5% with each planning unit in Skyblue are protected by CCED or CPAD, (b) at least 30% of each planning unit in Skyblue are protected by CCED or CPAD.

3.2. Shifts in conservation prioritization due to environmental changes

The outputs from the species distribution model showed that climate change will negatively impact avian spatial and temporal distribution in terms of species richness (Supplementary Information Figures 5 and 6). The water allocation optimization model CALVIN revealed that climate change will cause the conservation use water cost to increase in most areas of the Central Valley (Supplementary Information Figure 7). Therefore, spatial plans designed with different climate scenarios differed from each other and formed delineable clusters for different climates (Figure 4). Compared to historical conservation solutions scenarios, the conservation solutions to the hot-dry condition had a greater heterogeneity than the warm-wet condition. They shared similar heterogeneity with historical conditions based on the Kappa coefficient matrix.

To identify representative conservation solutions under different climate scenarios, we constructed a Jaccard dissimilarity matrix and applied k-means clustering. The analysis revealed distinct solution clusters corresponding to each climate scenario, particularly when conservation targets were set at 30%. Specifically, the k-means algorithm identified three clusters (k=3), with the "hot" climate scenario diverging more significantly from the "warm" scenario than from the historical baseline. Medoid configurations of each scenario's prioritization highlighted distinct spatial patterns of flooded habitat in the Sacramento and San Joaquin Valleys under future climate conditions compared to historical levels. Notably, climate change scenarios required greater spatial connectivity among flooded habitats. Under historical conditions, four major flooded regions remained disconnected, whereas in future scenarios, areas such as Red Bluff and Corning—previously excluded—became high-priority zones.

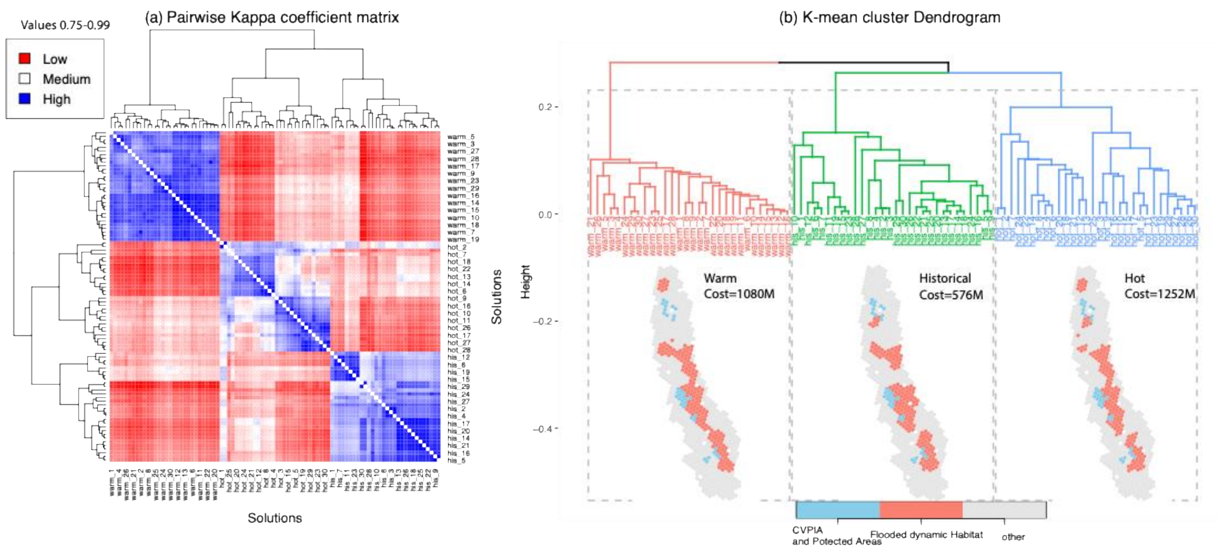

Figure 4. Spatial configuration for different climate change scenarios with 30% conservation targets: a) pairwise kappa coefficients matrix for spatial dissimilarity test, b) cluster dendrogram for similarity clustering with cluster medoid solutions

When conservation targets were reduced to 20%, spatial disparities across climate scenarios became more pronounced as reflected by increased Jaccard distances (Figure 5b). The k-means cluster analysis found five clusters (k=5) with high variability in spatial configuration, even within the same scenario. This reflects the variable temporal and spatial distribution of conservation features due to climate change. The reduction in conservation targets also decreased the irreplaceability of certain planning units, amplifying spatial divergence among scenarios. Interestingly, less extreme warm-wet scenarios introduced more variability in spatial configurations than the hot-dry scenario. Some warm-wet solutions closely resembled historical patterns, while others represented the most significant departures. Overall, climate scenarios that diverge more strongly from historical baselines necessitate higher spatial connectivity to meet conservation targets while minimizing land use. These findings underscore that climate change introduces significant variability into conservation prioritizations across California's Central Valley. To ensure the continued effectiveness, this research provides the spatial explicit information for conservation activities in California, and a practical framework for conservation planning beyond California that are facing similar challenges of maintaining sustainability in multiple aspects of landscapes, such as water, agriculture, and biodiversity.

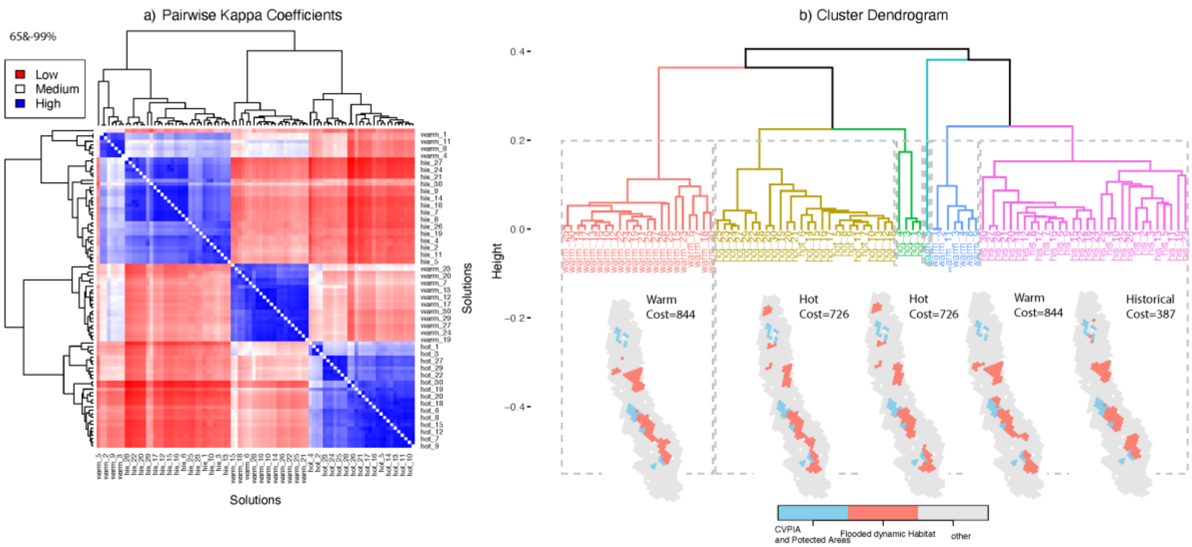

Figure 5. *Spatial configuration for different climate change scenarios with 20% conservation targets: a) pairwise kappa coefficients matrix for spatial dissimilarity test, b) cluster dendrogram for similarity clustering with cluster medoid solutions.*

3.3.Trade-offs in conservation objectives and costs

Multi-benefit planning also means finding the tradeoff points where the cost-effectiveness of conservation resources spent is the highest. The tradeoff analysis showed that when the budget was lower than 957 million, conservation areas were concentrated in the San Joaquin Valley, based on the maximum features prioritization with varying budgets under warm-wet scenario (Figure 6) (historical scenarios in supplementary information Figure 6). Kern County lands were most selected when the conservation cost is constrained at 957 million dollars, considering both water and foregone agricultural costs. The groundwater recharge benefit is around 1029 kaf. When the conservation budget reached the 1555-million-dollar threshold, the investment started to be able to afford flooded habitats in the Sacramento Valley, surrounding both the CVPIA refuge concentrated areas north (Sacramento and Colusa National Wildlife Refuge, etc.) and south (Volta and Mendota wildlife Refuge, etc.) to the Delta. At the same time, the selected areas in the San Joaquin Valley shifted north to Kaweah and Kings Counties. The conservation investment became less cost-effective after the budget exceeded 1675 million dollars annually. There were barely any increases in feature protection percentages with increasing investments once all the CVPIAs in the San Joaquin Valley were spatially connected. Planning units within the parcels were replaced with relatively more costly but higher feature units if the budget was bigger than 1675 M. Additional trade-off relations between conservation targets and conservation benefits were analyzed and provided in Supplementary Information. Higher conservation costs would support higher conservation targets with almost linear relations based on our relative penalty values. However, this linearity cannot be maintained if the assumed connectivity in prioritization is unrealistic because of real-world land use constraints. Feature representation cost-effectiveness may start to decline when exceeding a specific target value.

Climate change and prioritizing environmental flows in California could bring agricultural land out of production, particularly in the San Joaquin Valley. However, the fallow land may not exceed 900 thousand acres, considering that water trading and conjunctive use may further bring this number down (Escriva-Bou et al., 2023). Therefore, we set a 20%-25 % target for the conservation prioritization that minimizes cost and used 957 and 1436 million dollars as budget constraints for the conservation benefit maximum feature problem to restrict water and land resources use. The spatial configuration of the prioritized dynamic habitat areas for these varying targets was provided in Supplementary Information Figure 10.

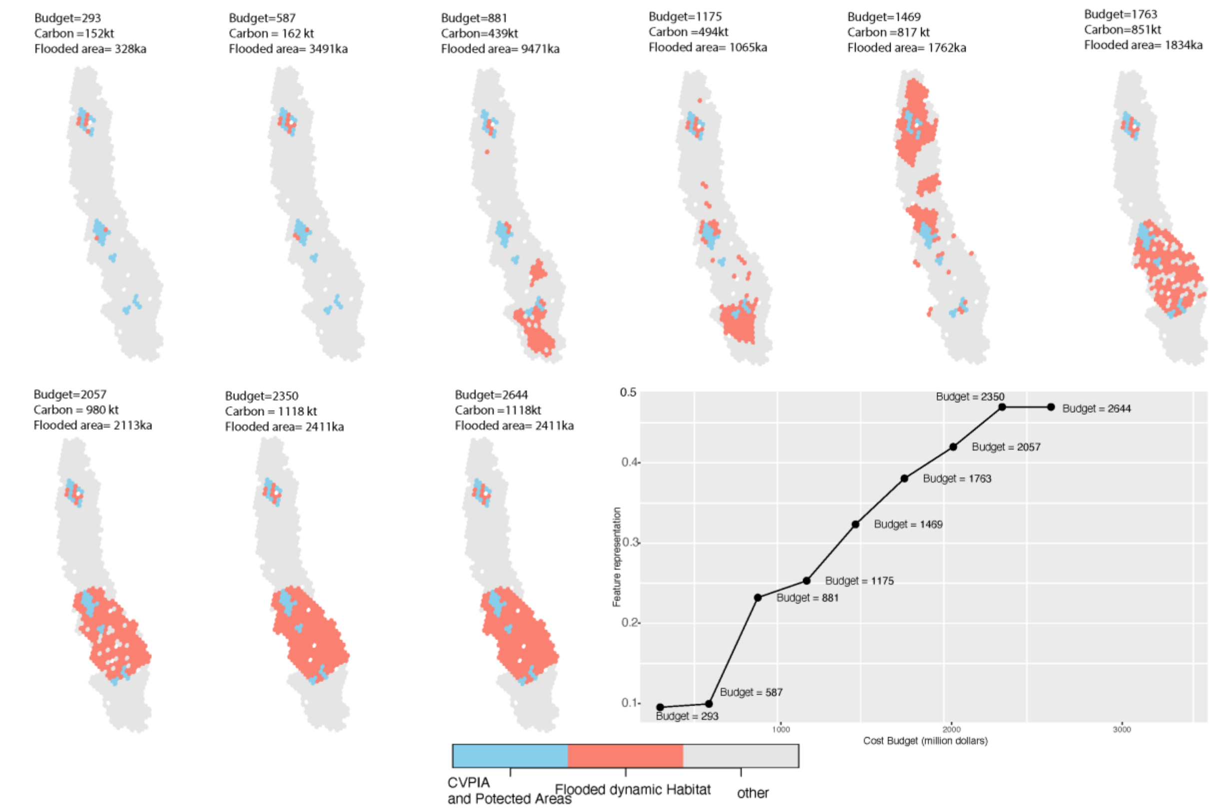

Figure 6. Spatial configuration of flooded habitats and feature representations with varying conservation investment budgets.

3.4.Cost savings in multi-benefit dynamic habitats conservation planning

Configurations of the prioritized areas based on different features contrast strongly, with carbon sequestration features defining the shape of conservation areas to the greatest extent (Figure 7). The irreplaceability became very high in Kern, Tule, and Tulare counties when the carbon sequestration feature was added to the birds' abundance feature (0.8-0.9). These areas have a very high density of croplands, enhancing carbon sequestration. However, the foregone agricultural cost is low because the value of hay crops for dairy products is low. If the foregone values for ranching are considered, it will probably affect the cost-effectiveness.

Bird abundance-configured prioritization covers most of the groundwater recharge feature-configured conservation prioritization. Adding groundwater recharge to bird conservation doesn't change the prioritization spatial configuration as much as the carbon sequestration feature did. Groundwater recharge features favor the southern Central Valley and the San Joaquin Valley. The "Birds+groundwater recharge" scenario has lower replaceability than the "Recharge" only scenario in most of the planning units. That is, prioritization can trade off the significance of some features for others when there are more features in the selection criteria.

Multiple objectives co-optimizing different benefits can achieve significant cost savings, as presented in the conservation costs for each scenario. Groundwater recharge and bird conservation co-benefit scenarios have even lower conservation costs than groundwater recharge alone. Conserving all three features only adds 13% to the cost of conserving birds and groundwater, and the cost remains the same as conserving birds and carbon only.

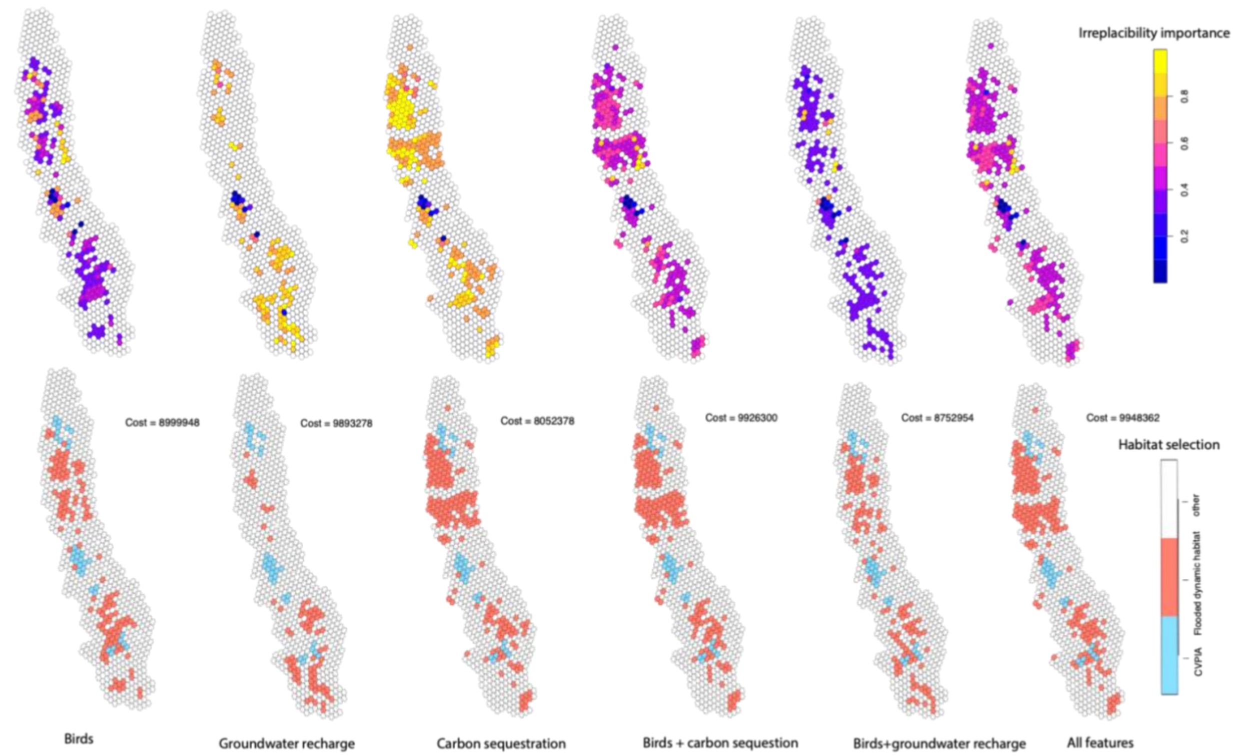

Figure 7. Irreplaceability importance (Top) and spatial configuration (Bottom) of habitat prioritization over different conservation features scenarios

There are also cost savings in a dynamic habitat vs a static conservation approach. Central Valley's winter has relatively more important roles in providing stopovers for birds migrating from Alaska to their breeding destination. At the same time, flooding attenuation needs in the Central Valley are also high in winter (Mount et al., 2023). Varying the targets across different seasons with a conservation focus on winter can potentially cut down costs with equal conservation outcomes. Based on the 90/20 rules (SWRCB, 2011), it is less environmentally impactful to divert surface water during December to March. Therefore, we set December-March with 40% targets and the rest of the months with 10 % targets to lower the foregone agricultural costs. Recharging groundwater during winter also helps flood attenuation (Peterson & Bardeen, 2023). Based on the monthly configuration of spatial prioritization based on historical species distribution and costs, the annual cost is 10.2 million dollars (Supplementary Information Figure 11a), which is only 10% of the cost of static habitat configuration and triple the feature coverage compared to CVPIA refuges (Supplementary Information Figure 11b).

3.5.Spatial and temporal co-optimized dynamic habitats

Based on temporal and spatial conjunctive prioritization, we found that November and December in the Sacramento Valley, and December and January in the San Joaquin Valley, were the most preferred months for creating dynamic flooded habitats when flexible targets were set (without specifying targets for specific months) (Figure 8). Spatial configuration agreed with the static habitat configuration; however, the conservation efficacy is higher than the static configuration, increased from 39% median coverage to 42% median coverage, and tripled conservation coverage compared to existing CCED and CPAD protected areas. When fixed equal targets each month, planning units with extremely high values up to 100% were selected, which were also not selected because of spatial connectivity and investment constraints in other scenarios. We also concluded that spatial and temporal conjunctive connectivity can synergize and increase conservation benefits. Specifically, adjacent planning units don't have to be flooded simultaneously to create spatial connectivity if the neighboring unit was flooded in the previous month.

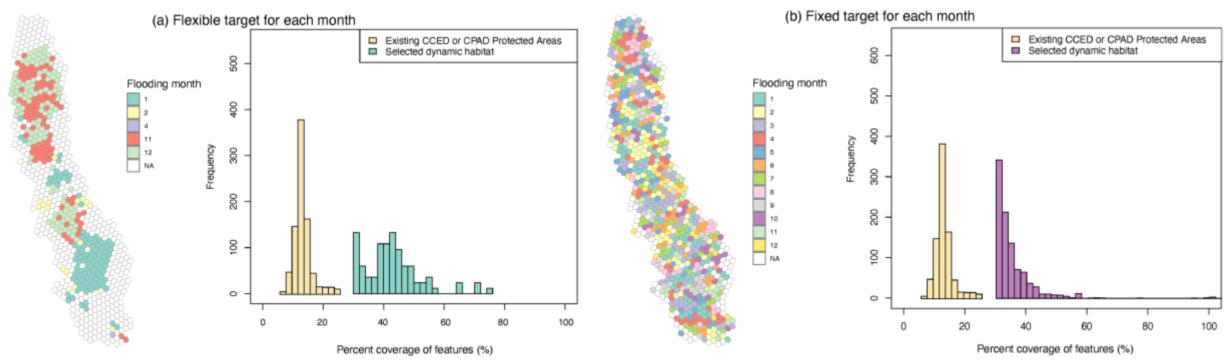

Figure 8. Configuration of spatial and temporal conjunctively prioritized flooded months and locations assigned to planning units and their feature representations with (a) flexible targets across months and (b) fixed targets across months

4. Conclusion

The current CCED and CPAD areas do not sufficiently protect key conservation features. Conserving cultivated lands with scheduled land and water use is particularly challenging and often cost-prohibitive. This research adopts a forward-looking approach to identify conservation strategies that account for projected species distributions, future water costs, and anticipated land use changes.

We employed a spatial and temporal conjunctive prioritization framework and developed a novel multi-zone optimization method incorporating monthly variation in conservation features and costs. This approach enhances synergistic spatial and temporal connectivity, enabling mutual reinforcement of conservation benefits. While high-coverage planning units tend to be expensive, conjunctive prioritization makes them more cost-effective. Transitioning from static to dynamic habitat management can further improve conservation outcomes, achieving similar or better biodiversity coverage at just 10% of the cost of traditional static approaches. In the face of escalating environmental and human pressures, multi-benefit conservation strategies that support wildlife, agriculture, and water systems are the most sustainable path forward (Peterson & Bardeen, 2023).

In California's Central Valley—a Mediterranean climate region critical for agricultural production and food security—there is a substantial unmet need for shorebird habitat. Strategically creating flooded habitats at the right time and in the right place can yield multiple co-benefits: supporting wildlife, benefiting farmers, mitigating greenhouse gas emissions, and recharging groundwater. Seasonal groundwater recharge during wet periods can sustain critical habitats during dry spells, with some recharge zones showing enhanced habitat potential. Dynamic flooded habitats) support the highest densities of wintering waterfowl found anywhere in the world (CDFW 2019). This research identified such priority areas for the dynamic flooded habitats to help guide resource allocation and water use decisions.

However, realizing these co-benefits faces logistical and administrative hurdles. Coordination among surface reservoirs, recharge operations, and infrastructure limitations constrains the ability to move water efficiently to target locations. Moreover, permitting processes are often lengthy. While this study does not quantify these administrative costs, it provides a numerical foundation for ongoing stakeholder discussions. Decision-makers, agencies, and communities are central to refining groundwater sustainability agency (GSA) plans and the spatial configuration of conservation zones.

Climate change is expected to reshape the spatial patterns of cost-effective conservation. Under hot-dry scenarios, conservation priorities shift more dramatically than under warm-wet scenarios, with the latter producing greater disparities across biodiversity targets. Across all climate change scenarios, conservation planning exhibits increased variability and demands higher spatial connectivity to meet the same biodiversity goals as under historical conditions.

Systematic Conservation Planning (SCP) remains a powerful tool for integrating conservation actions with resource constraints and diverse target objectives. Yet, SCPs that overlook climate-induced changes in species distributions and community composition risk identifying areas that may not remain viable in the future. Furthermore, conservation efforts incur real economic costs. Accurately estimating these costs is crucial for balancing trade-offs between human land use and conservation outcomes. By using forward-looking spatial and temporal (STE-SCPs), conservation investments made today can remain effective in the projected changing environments.

Data Availability

All data used are open-source data and cited when used in the manuscript, and project-specific data will be stored on Zenodo with code.

Code Availability

The code for the spatial prioritization and producing the figure is available in a GitHub repository https://github.com/lily6966/dynamic-habitat-prioritization and will be documented on zenodo.

Supplementary Information

Supplementary Information is provided with the publication.

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