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RESEARCH

Flooded Wetland Availability for Breeding Waterfowl in a Mediterranean Climate: Mapping 38 Years of Historical Data in Suisun Marsh, California

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ABSTRACT

Most managed wetlands in California are ephemeral and are purposefully flooded during the fall and winter for over-wintering waterfowl, and are dry during the spring and summer waterfowl breeding season. Only semi-permanent and permanent wetlands remain flooded through the critical summer brood-rearing period for ducklings. We examined the availability of flooded wetlands for breeding waterfowl in the brackish Suisun Marsh (California, USA) annually during the spring (April 27–May 17, during peak nesting) and summer (June 17–July 7, during peak duckling brood rearing), for a 38-year period using Landsat satellite imagery and spectral mixture analysis. Flooded wetland area increased 43% in spring and 48% in summer from 1984 to 2021 but varied among years (spring: 37.6–88.6 km^2; summer: 17.7–57.5 km^2). This increase in flooded wetland area over the past 4 decades was due to just a few sites, with only 24% (spring) and 15% (summer) of the 198 land-owner parcels increasing in flooded area. Flooded wetland area in the spring was unrelated to annual precipitation between October and April (range: 25–104 cm) or spring precipitation between January and April (range: 8–65 cm), whereas flooded wetland area in the summer was weakly correlated to both annual and spring precipitation. Flooded wetland area in spring and summer was also weakly correlated with the median daily outflow from the Sacramento–San Joaquin River Delta between March 15 and June 15, which corresponds to a critical period of wetland water management for breeding waterfowl. Our results indicate that spring and summer flooded wetland habitat for breeding waterfowl has increased slightly over the past 4 decades, varies annually, and mostly depends on local wetland management practices rather than on precipitation or Delta outflow. Managing habitats as semi-permanent wetlands would increase flooded wetland habitat in the spring and summer, and provide habitat for nesting hens and ducklings.

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KEY WORDS

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INTRODUCTION

Wetlands are an imperiled but critical habitat for a variety of aquatic species (Wilen and Frayer 1990). Wetland habitats in California support waterbirds (waterfowl, shorebirds, and wading birds) that migrate within the Pacific Flyway as well as providing critical habitat for species that breed within the state. The majority of historical wetland habitat has been lost as a result of human development, and existing wetlands face future threats from drought, sea level rise, and other consequences associated with a changing climate (Heitmeyer et al. 1989; Wilen and Frayer 1990; Thorne et al. 2018). Within California, more than 91% of the original wetland habitat has been lost (1780 to 1980; Dahl 1990), and more recent studies show freshwater wetland habitat area continues to decrease within coastal watersheds (Dahl and Stedman 2013). Decreased flooding of wetland habitats in regions that support waterbird migration or breeding activities can negatively affect populations (Donnelly et al. 2019).

During the waterfowl breeding season, the consistent presence of flooded wetlands is critical for ducks during nesting and brood rearing. Dabbling duck hens often nest in upland habitats and take daily breaks from incubation to forage in nearby managed wetlands (Casazza et al. 2020; Croston et al. 2021). After the eggs hatch, hens move their broods to flooded wetlands where ducklings forage and remain for 48 to 60 days until they gain the ability to fly (Bellrose 1976; Mauser et al. 1994; Chouinard and Arnold 2007; Casazza et al. 2020; Casazza et al. 2021; Peterson et al. 2024a). Sensitivity analyses show that population growth rates of mallards are influenced the most by breeding parameters, including the survival of nests, ducklings, and breeding hens (Johnson et al. 1987; Hoekman et al. 2002; Coluccy et al. 2008). The availability of flooded wetlands and their proximity to nesting sites during this critical life-history stage can affect reproductive success (Chouinard and Arnold 2007; Peterson et al. 2024a). At the continental scale, mallard nesting effort and population recruitment decrease when there are fewer flooded wetlands available in the spring (Krapu et al. 1983; Cowardin et al. 1985; Johnson and Grier 1988). Furthermore, limited availability of flooded wetlands in the summer can be a major contributor to low duckling survival rates (Rotella and Ratti 1992; Hoekman et al. 2004; Garrick et al. 2017) and a decrease in population recruitment (Hoekman et al. 2002; Amundson et al. 2013). The breeding populations of mallard and gadwall in California have declined (Ackerman et al. 2014; Brady and Weaver 2022, 2023) and are currently below the Central Valley Joint Venture's breeding population objectives (CVJV 2020). Thus, quantifying flooded wetland area in the spring and summer is important when examining temporal trends in local waterfowl reproduction.

Suisun marsh, a complex of tidal and managed wetlands (hereafter referred to as Suisun Marsh[1]) located in the upper San Francisco Estuary in California, USA, is one of the largest brackish marshes in western North America and comprises approximately 12% of the wetland habitat that remains in the state of California (Ackerman et al. 2014). The availability and quality of flooded wetland habitats within Suisun Marsh affect many different species that rely on managed wetlands, including waterbirds, mammals, and reptiles (Smith et al. 2020; Agha et al. 2020; Peterson et al. 2021; Schacter et al. 2021). Upland habitats within the boundaries of Suisun Marsh contain high nesting densities of dabbling ducks (McLandress et al. 1996; Ackerman et al. 2014) that rely on flooded wetlands to be available throughout the spring and summer waterfowl breeding season. Within Suisun Marsh, the flooded wetland area on Grizzly Island varied substantially among years (Schacter et al. 2021), and the proximity of flooded wetlands to upland nesting habitat may influence duckling survival rates (Ball et al. 1975; Chouinard and Arnold 2007; Peterson et al. 2024a). Many seasonal wetlands in Suisun Marsh are managed to produce food resources and habitat for wintering waterfowl, although individual wetland management decisions can vary from year to year. Fall and winter-flooded seasonal wetlands may undergo multiple leach cycles in the spring and summer to

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[1] The difference in the spelling of "marsh" and "Marsh" here is taken from internal USGS usage followed by SP. The spelling is intentional, not typographical errors, and do not conform to *SFEWS style and usage*.

irrigate wetland plants and control soil salinities and then require a period of dry conditions for seed germination and seedling growth as well as for maintenance operations, which makes these seasonal wetlands unflooded during the waterfowl breeding season.

Water management for wetlands in Suisun Marsh is guided by a combination of environmental considerations (e.g., salinity of available water), decisions made by private and public water and land managers, and existing infrastructure. Suisun Marsh comprises a managed network of seasonal wetlands and tidal sloughs, and 90% of the marsh plain is diked (Manfree 2014). Suisun Marsh has a Mediterranean climate, with most of the precipitation occurring each year between October 1 and April 30 (mean ± SD: 93.7% ± 6.1%; *https://cdec.water.ca.gov*; Napa weather station; accessed May 6, 2022) and very dry summer months. Thus, the area of flooded wetlands during the spring and summer is likely determined mostly through management decisions to move water on the landscape. Legally mandated salinity and water-quality thresholds guide how freshwater is released into the Suisun Marsh from the upstream Sacramento–San Joaquin River Delta and moved through the marsh by the Suisun Marsh Salinity Control Gates on Montezuma Slough and other water-delivery facilities during specific times of the year (SWRCB 2018). The Salinity Control Gates, built between 1980 and 1990 by state and federal water projects, influence the flow of water within Suisun Marsh to reduce higher-salinity water from flowing into the marsh on flood tides, with the goal of improving habitat conditions for permanent and seasonally managed wetlands, although the Salinity Control Gates typically only operate from October through May (Sommer et al. 2020). In 1996, a diversion fish-screening program was implemented by the Suisun Resource Conservation District (SRCD, *https://suisunrcd.org/*) at multiple diversion sites along Montezuma Slough. These fish-screening facilities allowed some wetland managers access to water for habitat management during periods of diversion restrictions or closures that were implemented to protect fish species listed in 1994 under the Endangered Species Act from entrainment (2024a email between S. Chappell, SRCD, and SP, unreferenced, see "Notes"). Additionally, starting in 1998 to 2003, private and state entities have used incentive programs and provided grants to improve water-delivery infrastructure and encourage landowners to retain more flooded wetlands during the waterfowl breeding season for production of ducklings (2024b in-person conversation between S. Chappell, SRCD, and SP, unreferenced, see "Notes").

The objectives of this study were to quantify flooded wetland availability for breeding waterfowl during a 38-year period from 1984 to 2021 in Suisun Marsh. We used remote sensing to identify non-tidal water bodies—including seasonal, semi-permanent, and permanent wetlands—at multiple spatial extents. Specifically, we examined whether the availability of flooded wetlands has changed substantively over the past 38 years during the spring (peak waterfowl nesting) and summer (peak waterfowl brood rearing). Additionally, we examined temporal trends for individual land parcels as well as geographic regions within Suisun Marsh to identify more localized trends in the availability of flooded wetlands for breeding waterfowl. Lastly, we tested whether flooded wetland area within Suisun Marsh was related to precipitation or freshwater outflow from the Sacramento–San Joaquin River Delta or, instead, was more driven by local management decisions.

MATERIALS AND METHODS

Spectral Mixture Analysis

We digitized water on the landscape for breeding waterfowl and other wetland-associated species within Suisun Marsh during a 38-year period with remote sensing methods that combined Landsat satellite imagery (composite images; EROS Center 2020a, 2020b, and 2020c) and spectral mixture analysis using Google Earth Engine (*https://earthengine.google.com*; Adams and Gillespie 2006; Gorelick et al. 2017; Donnelly et al. 2019). Spectral mixture analysis is useful for heterogeneous landscapes because it can estimate the proportion of each pre-identified class of landscape cover (e.g., water, bare ground) within each 30 × 30-m Landsat pixel (Adams and Gillespie 2006). Following the methods and modified code for Google Earth Engine from Donnelly et al. (2019), we used spectral mixture analysis to detect water that could provide flooded wetland habitat for breeding waterfowl within Suisun Marsh in the upper reaches of the San Francisco Estuary, California, USA from 1984 to 2021 at two times each year that corresponded to peak nesting (spring) and peak brood rearing (summer; McLandress et al. 1996).

To train the Google Earth Engine algorithm to the spectral profiles of different landscape cover types, we first identified surface material categories with unique spectral signatures (endmembers) of bare ground, shrub/tule, and upland vegetation within the boundaries of Suisun Marsh, following the methods used by Donnelly et al. (2019). We digitized polygons for these endmember classes using the Google Earth Engine satellite base map and placed them in areas where the endmember classes appeared to be homogenous. Additionally, we identified endmember classes of water and green vegetation using the Normalized Difference Water Index (NDWI) to identify surface water, and the Normalized Difference Vegetation Index (NDVI) to identify green vegetation, using the 99th percentile values from each index to identify the endmember category. Using the composite image from each year and time-period to determine the values that identified endmember categories allowed for dynamic changes among years. We used the function ‘img.unmix’ in Google Earth Engine and the spectral profiles of the five identified endmember classes to decompose a collection of Landsat 5 (1984–2011), 7 (2012), and 8 (2013–2021) images into endmember classes (EROS Center 2020a, 2020b, 2020c). The spectral mixture analysis provided a proportion of each endmember in each 30 × 30-m Landsat pixel, and we selected the values for the water endmember class.

Validation of Water Maps from Spectral Mixture Analysis

We validated the identification of water from the spectral mixture analysis using Landsat imagery against seven hand-digitized water maps previously published by Schacter et al. (2021) for Suisun Marsh during May (2016, 2017, 2019) and July (2016, 2017, 2018, 2019). The hand-digitized water maps were created by visual observation of multiple high-resolution, multi-spectral images for each time-period, and were verified by ground-truthing when needed (Schacter et al. 2021). We were unable to include the May 2018 time-period from Schacter et al. (2021) in our method validation because there were no cloud-free Landsat images that corresponded to the time-period for that specific hand-digitized map. Spectral mixture analysis was run on a composite of the best available, cloud-free, Landsat imagery within a ± 10-day window of the date used to generate each hand-digitized water map in Schacter et al. (2021) (Table 1), where each pixel in the composite received the mean value of the spectral bands from the set of Landsat images within this 21-day window (typically $n = 1$ to 2 because of the Landsat 16-day return interval). We converted each hand-digitized water map into a raster layer that aligned with the 30 × 30-m grid cells from the Landsat imagery, and used the percentage of each pixel that overlapped with a hand-digitized water polygon to assign each pixel as dry ($\leq 10\%$ overlap with a polygon from the hand-digitized water map) or wet ($> 10\%$ overlap with a polygon from the hand-digitized water map). We then compared the published hand-digitized water maps from Schacter et al. (2021) to the results from this current spectral mixture analysis to confirm that our spectral mixture analyses using Landsat images was accurate.

For the validation procedure, we used a digitized layer of water features from the Bay Area Aquatic Resources Inventory (BAARI; SFEI–ASC 2017) to exclude the bays, sloughs, tidal features, and water channels in Suisun Marsh from each raster of Landsat imagery and the hand-digitized water maps published by Schacter et al. (2021). Next, we randomly selected 500 wet and 500 dry pixels from each raster for each of the seven time-periods to compare with the corresponding values generated from the spectral mixture analysis. Then, we tested the accuracy of the spectral mixture analysis for the identification of

Table 1 Time-periods for the validation of spectral mixture analysis and the selection of the threshold for categorization of a pixel as wet (indicating water). Hand-digitized water maps were created by outlining water visible in multi-spectral satellite imagery through the Planet Open California Data portal (Planet Team 2017) and supplemented with lower-resolution, multi-spectral satellite imagery obtained through the USGS Earth Resources Observation and Science Center (EROS). The available Landsat imagery was composited from the best available images in the date range specified for spectral mixture analysis.

Year	Month	Date range: hand-digitized water maps	Date range: Landsat imagery for spectral mixture analysis	Number of images used in spectral mixture analysis
2016	May	June 1	May 22–June 11	2 (May 26, Jun 11)
2016	July	July 10[a], July 14	June 30–July 20	1 (July 13)
2017	May	May 17	May 7–27	1 (May 13)
2017	July	July 13	July 3–23	1 (July 16)
2018	July	July 16, July 19[a]	July 9–29	1 (July 19)
2019	May	May 5, May 12[a]	May 2–22	2 (May 3, May 19)
2019	July	July 15	July 5–25	2 (July 6, July 22)

a. Primary satellite image used for the time-period for hand-digitized water maps. The second date was a supplementary image to aid in the delineation of wetland boundaries in areas that were hard to see in the primary image.

water (wet) at various thresholds values (i.e., all values above the threshold would be categorized as water, and all values equal to or less than the threshold would be categorized as dry). For the wet class, the producer's accuracy is the count of sampled areas that were wet from the spectral mixture analysis and in agreement with the sampled wet areas from the Schacter et al. (2021) hand-digitized maps, divided by the total sampled areas that were wet from the hand-digitized maps (this includes areas that were classified as dry in the spectral mixture analysis) (Story and Congalton 1986). For the wet class, the user's accuracy is the count of sampled areas that were wet from the spectral mixture analysis and in agreement with the sampled areas that were wet from the Schacter et al. (2021) hand-digitized maps, divided by the total sampled areas that were classified as wet from the spectral mixture analysis (this included areas that were dry in the hand-digitized maps). Error matrices of producer and user accuracy were created for threshold values from 0.15 to 0.70 at intervals of 0.05 (see Figure A1 in Appendix A), and we selected 0.40 as the threshold value that maximized producer vs. user accuracy while remaining conservative for classifying a pixel as wet. Specifically, we decreased the likelihood of falsely identifying wet mud and very shallow, receding water as wet habitat that would be available for breeding waterfowl, which prefer wetland water depths > 15 cm (Colwell and Taft 2000; Isola et al. 2000; Peterson et al. 2024b).

Mapping Flooded Wetland Area for 38 Years

After the spectral mixture analysis was validated against the hand-digitized maps of Schacter et al. (2021) and after we established a threshold value of 0.40 to use for identification of water within a 30 × 30-m Landsat pixel, we conducted a spectral mixture analysis twice each year during the waterfowl breeding season on composite Landsat imagery over a time-series from 1984 to 2021. We quantified the flooded wetland area during waterfowl breeding in Suisun Marsh each year for two 21-day temporal windows, centered on May 7 (April 27–May 17; hereafter spring wetland availability) and on June 27 (June 17–July 7; hereafter summer wetland availability), by first making a composite of all existing imagery of Suisun Marsh taken during those time windows for each year. Selecting these dates allowed us to obtain complete satellite coverage of Suisun Marsh for the greatest number of years with temporally comparable data. Waterfowl nesting season in Suisun Marsh typically begins in late March (McLandress et al. 1996; Ackerman et al. 2003). From 2010 to 2019, the spring wetland availability time-frame represented peak nesting and the start of duckling brooding. During this time window, 38% of all waterfowl nests were initiated, and 16% of successful nests hatched.

By the end of this window (May 17), 73% of all nests had been initiated for the season, and 19% of successful nests had hatched. From 2010 to 2019, the summer wetland availability time-frame (June 17–July 7) represented peak duckling brooding. During this time window, 20% of all successful nests hatched. By the end of this time window (July 7), 98% of all nests had been initiated and 87% of successful nests had hatched, but most ducklings had not yet fledged (Ackerman et al. 2015). For both the spring and summer availabilities of flooded wetlands, we ran spectral mixture analysis on a composite of the best available, cloud-free pixels from Landsat imagery within the 21-day windows. We created composite Landsat images by taking the mean pixel values for spectral bands among the multiple images that existed for a time-period, and excluding any pixels that were masked out of an image as a result of cloud cover. For the spring 1994 map, we manually removed the entire image from May 14, because of cloud-cover interference, and relied solely on the image from April 28 for that time-period instead of a composite image. For the summer maps, images from 1995 (June 18), 2007 (June 19), and 2008 (June 21) were manually removed because of cloud-cover interference, and we only used the July 4 (1995), July 5 (2007), and July 7 (2008) images for those time-periods, respectively. In all other cases, we used all the available Landsat images during these time-periods ($n = 1$ to 2 images) for each year to create the composite Landsat image for the spectral mixture analysis. If only one image for a time-period was available, we used that image.

We defined four spatial extents to calculate flooded wetland availability (Figure 1). For the largest spatial extent, we used the California Department of Water Resources (CDWR) GIS layer for Suisun Marsh (*https://cdec.water.ca.gov*) to establish an outer boundary, and excluded land parcels at the edge that were not water and were not classified as managed wetlands, permanent water, tidal marsh, or uplands (Casazza et al. 2021). Second, at a smaller spatial scale, we established a boundary for Grizzly Island, using the edge of the adjacent Grizzly Bay, Honker Bay, and Montezuma Slough to form the border; Grizzly Island is the site of several long-term waterfowl nesting studies, and comprises approximately 50% of the managed wetlands in the Suisun Marsh (Schacter et al. 2021). We then defined two spatial extents by the upland habitat on Grizzly Island known to be used for nesting by waterfowl (primary and core extents). Within Grizzly Island, we first established the primary extent to represent the largest area of upland habitats that provide nesting sites and include many of the units historically managed by the California Department of Fish and Wildlife (CDFW) at the Grizzly Island Wildlife Area for waterfowl nesting (Ackerman 2002) and four private duck clubs adjacent to the Grizzly Island Wildlife Area. We buffered those upland habitats by a distance of 1 km (Figure 1) because the probability of a brood surviving the move from the nest in upland habitat to a nearby wetland dropped to $< 50\%$ when the nearest flooded wetland was > 1 km from the nest (Peterson et al. 2024a). Within the primary extent of upland nesting, we established the core extent to represent the central and most contiguous portion of upland habitats that were managed and monitored for nesting ducks on Grizzly Island from 2015 to 2019 (Grizzly Island Wildlife Area, Fields 11N, 13A-O, 14A-P, 15; and the upland nesting habitat within three private duck clubs that border the Grizzly Island Wildlife Area's Fields 13A-L). We also buffered the core extent of upland nesting by 1 km. The extent of each buffer around upland nesting habitat was trimmed to the boundary of Grizzly Island, such that the polygon was not allowed to extend into the adjacent slough or bays (i.e., non-wetland habitat). For all spatial extents, we identified and excluded bodies of water that are not typically used by breeding waterfowl (Casazza et al. 2021; Schacter et al. 2021). Bodies of water excluded from wetland availability calculations included the bays adjacent to Grizzly Island (Grizzly Bay, Honker Bay), tidal mudflats, tidal marsh, tidal lagoons, and the network of large tidal sloughs throughout Suisun Marsh (e.g., Montezuma Slough; Figure 1). We used the BAARI base layer (SFEI–ASC 2017) to identify, add a 20-m buffer, and remove the buffered water bodies from every composite

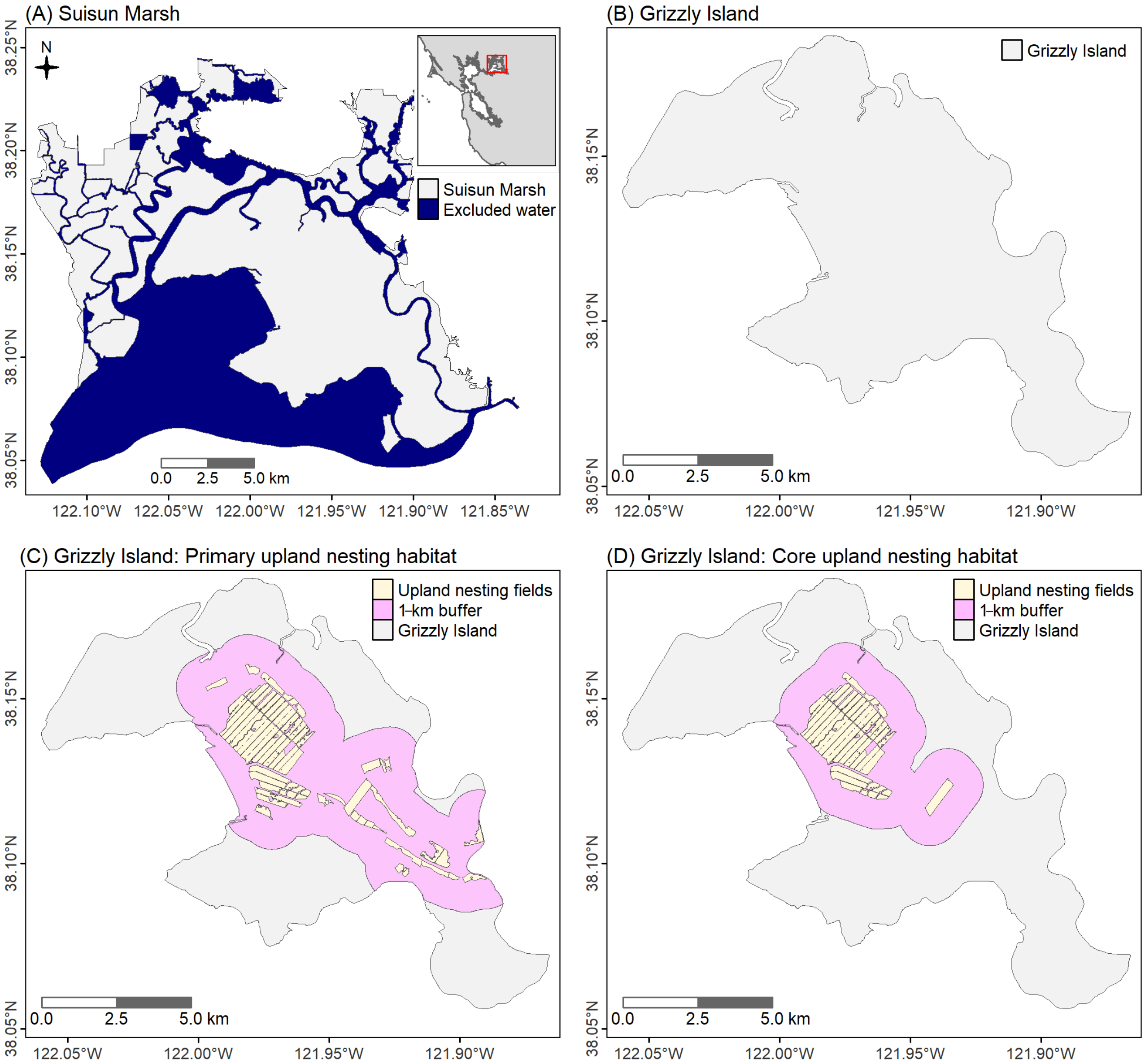

Figure 1 Spatial extents examined for available flooded wetland area in Suisun Marsh (California, USA). (**A**) Suisun Marsh, with the excluded water category indicating the permanent water bodies and tidally-influenced sloughs that were removed from all calculations of available wetland area for breeding waterfowl. Within Suisun Marsh, we quantified wetland area at three smaller spatial scales including (**B**) Grizzly Island, (**C**) a buffer of 1 km around the primary upland nesting habitats for dabbling ducks on Grizzly Island, and (**D**) a buffer of 1 km around the core upland nesting habitats for dabbling ducks on Grizzly Island.

image before we calculated the area of available water for breeding waterfowl (km^2).

Once we had the extent of all composite images that were analyzed using spectral mixture analysis (for each year and time-period) clipped to all four spatial extents (defined above), we examined the percent of missing data (obscured by clouds) within each composite image. Any composite image that was missing > 5% of the Landsat pixels was excluded from future analyses. For composite images that were missing < 5% of pixels, we applied a correction factor by assuming the percent of wet pixels in the missing data was proportional to the percent of wet pixels in the existing data.

Precipitation Over 38 Years

Suisun Marsh has a Mediterranean climate, where precipitation falls as rain during winter months and summer months are very dry. We downloaded precipitation data for water years from 1984 to 2021 from the California Data Exchange Center (CDEC, *https://cdec.water.ca.gov*; accessed May 6, 2022) from the two closest, long-term weather stations located in the San Francisco Estuary hydrological area: Fairfield (FRF—operated by the National Weather Service; latitude 38.267° longitude –122.067°) and Napa (NSH—operated by Napa County; latitude 38.283°, longitude –122.267°) weather stations. Precipitation was assessed for two time-periods: (1) starting October 1 of the prior year (start of the annual water year as defined by the state of California water agencies) and ending April 30 of the current year, before the peak of waterfowl nesting (hereafter annual precipitation), and (2) the winter and spring precipitation starting on January 1 and ending April 30 (hereafter spring precipitation), which may be the timing of precipitation more meaningful for nesting ducks (McLandress et al. 1996). We reviewed monthly precipitation records for missing data; we could not calculate annual and spring precipitation values if a month of data was missing. Although the Fairfield weather station was located closer to the center of Suisun Marsh, 24% of years had at least 1 month of precipitation data missing. The annual precipitation values for both stations were highly correlated ($R^2 = 0.93$, $p < 0.001$; Fairfield precipitation [cm] = 0.98 * Napa precipitation [cm] – 3.82), and the spring precipitation (January 1–April 30) values for both stations were also highly correlated ($R^2 = 0.91$, $p < 0.001$; Fairfield precipitation [cm] = 0.98 * Napa precipitation [cm] – 3.26). Thus, we calculated the average annual and spring precipitation values using the data from both weather stations and interpolating any missing data using a single station's data. Specifically, for cases when precipitation values were missing for a month from the Fairfield weather station, we multiplied the Napa precipitation value for that month by 0.98 and subtracted a correction factor (half of the intercept value from the correlations between weather stations: 1.91 cm for annual precipitation and 1.63 cm for spring precipitation).

Delta Outflow and Water Year Type Over 38 Years

To represent the rate of freshwater flowing out of the Sacramento–San Joaquin River Delta and past Suisun Marsh and into San Francisco Bay, we downloaded net daily Delta outflow for the Sacramento–San Joaquin River Delta (hereafter Delta outflow) calculations from the CDWR Dayflow model, estimated at Chipps Island, from the CDEC[2]. We used the daily Delta outflow estimates to calculate median daily Delta outflow for the period of March 15 to June 15 (hereafter, spring Delta outflow) during our 38-year study period, which is typically the time of year (after the waterfowl hunting season ends) when water managers actively move water on and off flooded wetland units in Suisun Marsh to leach salts from soils and provide flooded wetland habitats for breeding waterfowl (2024c videoconference among S. Chappell, SRCD, J. Takekawa, SRCD, and SP, unreferenced, see "Notes"). We also downloaded the water year classifications for the Sacramento Valley from the CDEC[2]. We used the water year classifications for the Sacramento Valley because the Sacramento River contributes 75% of the historical average annual flow from the combined Sacramento and San Joaquin River basins (Null and Viers 2013). Water year classifications for the Sacramento River hydrological basin were defined as (1) wet, (2) above normal, (3) below normal, (4) dry, or (5) critical, based on the annual Sacramento Valley Index for each water year, calculated by the CDWR (*http://cdec.water.ca.gov/cgi-progs/iodir/WSIHIST*).

Temporal Trends for Land Parcels and Regions Within Suisun Marsh

We examined temporal trends of wetland area for four spatial extents, 198 individual land parcels, and seven defined sub-regions within Suisun Marsh during spring and summer from 1984 to 2021 (Figure A2). We used the established land parcel boundaries mapped by

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[2] *https://cdec.water.ca.gov*

the Suisun Resource Conservation District (2024c in-person conversation between S. Chappell, SRCD, J. Takekawa, SRCD, and SP, unreferenced, see “Notes”), and we modified the land parcel ownership layer to include the main land management units of CDFW’s Grizzly Island Wildlife Area (Figure A2A). Sub-regions were delineated to represent different sections of the Suisun Marsh (Figure A2B). Following the same protocol described earlier, we used the BAARI base layer to exclude tidal mudflats, tidal marsh, tidal lagoons, and the network of large tidal sloughs throughout Suisun Marsh from analyses of available water for breeding waterfowl. We then used the modified boundaries to determine the area of available water in the composite Landsat images for each parcel and region for each year. As described above, we used a pixel threshold of 0.4 to identify each pixel as wet (>0.4) or dry (≤ 0.4). We only examined land parcels larger than 0.05 km^2. As described above, the composite image for any land parcel or sub-region that was missing $>5\%$ of the Landsat pixels was excluded from future analyses. For composite images that were missing $<5\%$ of pixels, the percent of wet pixels in the missing data was assumed to be proportional to the percent of wet pixels in the existing data.

Statistical Analysis

We quantified the arithmetic mean, standard deviation (SD), and coefficient of variation (CV) for wetland area in spring and summer from 1984 to 2021 at each of the four spatial extents, as well as for 198 land parcels and seven sub-regions. We used univariate general linear models to examine linear relationships between flooded wetland area (spring and summer) at all four spatial extents and (1) year, (2) precipitation, and (3) Delta outflow. We also used a one-way analysis of variance to test whether spring or summer flooded wetland area at the largest spatial scale (Suisun Marsh) varied among water-year hydrological classifications. Additionally, we examined whether flooded wetland area in the summer was correlated with flooded wetland area in the spring. We conducted all statistical analyses in the program R, version 4.4.0 (R Core Team 2024).

RESULTS

Between 1984 and 2021, the two waterfowl breeding seasons with the greatest amount of flooded wetland area in the spring (peak nesting; satellite imagery centered on May 7) at all spatial extents were 1998 and 2017; both years had widespread infrastructure failures and flooding that resulted in the overtopping of levees and inundation of areas that were not purposefully flooded. Thus, the water years of 1998 and 2017 and the corresponding flooded wetland areas quantified in the spring and summer were considered outliers for water management and were excluded from statistical analyses. The flooded wetland area data for all spatial extents, including 1998 and 2017, can be found in Peterson et al. (2025).

After removing those 2 years, we observed a 2.1-fold range between the minimum wetland area observed in the spring of 2004 (37.6 km^2) and the maximum wetland area observed in the spring of 2006 (77.4 km^2; Figure 2; Table 2; Figures A3 through A5 in Appendix A). During the summer (peak brood rearing; satellite imagery centered on June 27), we observed a 2.6-fold range between the minimum flooded wetland area that was observed in 1990 (17.7 km^2) and the maximum wetland area that was observed in 2006 (46.5 km^2; Table 2; Figure 3, Figure 4, Figure 5).

Temporal Trends in Wetland Area

During the waterfowl breeding season, flooded wetland area increased over time from 1984 to 2021 at most of the four spatial extents. We estimated that flooded wetland area in Suisun Marsh during the waterfowl breeding season increased over the study period (1984 to 2021) by 42.6% (18.1 km^2) in the spring ($R^2 = 0.32$, $p = 0.002$; Figure 6) and by 48.1% (11.1 km^2) in the summer ($R^2 = 0.21$, $p = 0.008$; Figure 7). At the next, smaller spatial scale, encompassing Grizzly Island, there was no temporal increase in wetland area among years in the spring ($R^2 = 0.07$, $p = 0.20$), but wetland area increased by 41.0% (5.1 km^2) over the 38-year period in the summer ($R^2 = 0.14$, $p = 0.035$). Flooded wetland area did not increase between 1984 and 2021 around the primary upland nesting habitat on

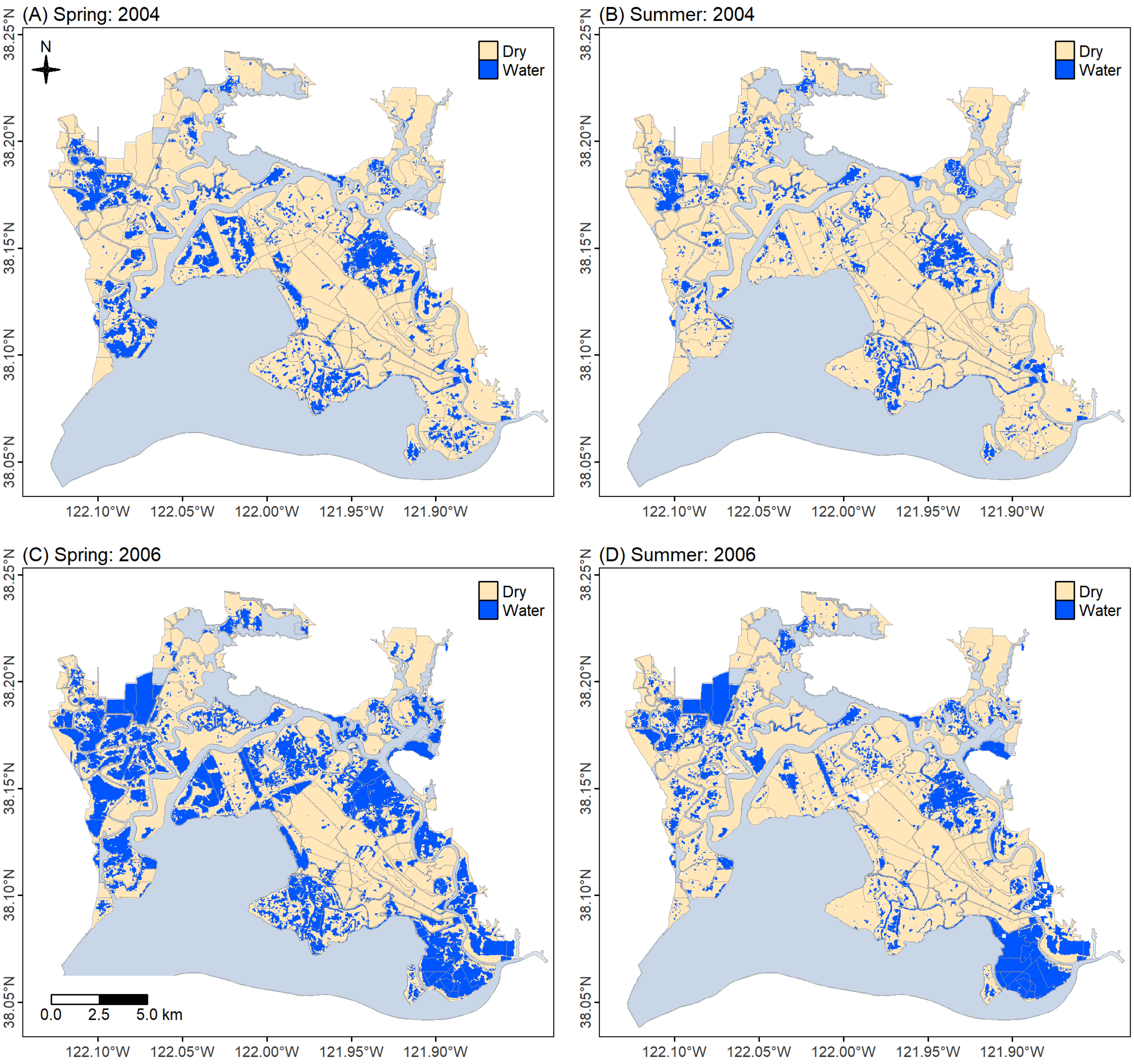

Figure 2 Flooded wetland area in Suisun Marsh during the spring (composite of satellite imagery from April 27 through May 17) and summer (composite of satellite imagery from June 17 through July 7) for the year with the (**A**) least amount of flooded wetland area (spring 2004) and (**C**) the greatest amount of flooded wetland area (spring 2006) during the 38-year study period from 1984 to 2021. The corresponding flooded wetland area in summer is shown in panels **B** (2004) and **D** (2006). Wetland area was identified using composites of Landsat imagery and spectral mixture analysis in Google Earth Engine (*https://earthengine.google.com*), with a pixel threshold of 0.4 used to categorize water (*blue*) versus dry land (*tan*). Any area within Suisun Marsh shown in *white* had missing data due to cloud cover. The large bays, tidal sloughs, tidal marsh, and tidal mudflats (*light blue gray shading*) that are not commonly used by breeding dabbling ducks were all excluded from calculations of flooded wetland area for breeding waterfowl. *Light gray lines* indicate land parcel boundaries.

Table 2 Flooded wetland area during spring (composite of satellite imagery from April 27 through May 17) and summer (composite of satellite imagery from June 17 through July 7) at four spatial extents in Suisun Marsh over a 38-year period (1984 to 2021). Values are mean ± standard deviation (SD), range, and coefficient of variation (CV) expressed as a percent. The water years of 1998 and 2017, which were excluded from statistical analyses, are excluded from mean and CV calculations but are included in the ranges. The spatial extents for the two Grizzly Island nesting areas include a 1-km buffer around the regions identified as either the primary upland nesting habitat or the core upland nesting habitat in Figure 1.

Spatial extent	Spring water availability (km^2)	Spring water range (km^2)	Spring water CV	Summer water availability (km^2)	Summer water range (km^2)	Summer water CV
Suisun Marsh	51.2 ± 9.8	37.6–88.6	19.2	28.9 ± 6.9	17.7–57.5	23.9
Grizzly Island	29.3 ± 5.0	19.9–49.5	17.2	15.3 ± 4.0	6.8–30.0	26.3
Grizzly Island primary nesting habitat	8.5 ± 1.6	5.4–18.8	18.7	5.0 ± 1.1	2.8–9.5	21.6
Grizzly Island core nesting habitat	4.2 ± 0.9	2.3–8.6	21.8	2.4 ± 0.6	1.3–4.2	25.2

Grizzly Island during either spring ($R^2 = 0.12$, $p = 0.08$) or summer ($R^2 = 0.02$, $p = 0.45$). However, at the smallest spatial scale, the average flooded wetland area around the core upland habitat on Grizzly Island increased by 47.0% (1.6 km^2) in the spring ($R^2 = 0.28$, $p = 0.004$) and 34.4% (0.7 km^2) in the summer ($R^2 = 0.12$, $p = 0.05$) from 1984 to 2021.

During the spring, 24.2% of the 198 individual land parcels ($n = 48$) increased in flooded wetland area over time, 70.2% ($n = 139$) did not have a detectable trend over time, and 5.6% ($n = 11$) decreased over time (Figure 8). During the summer, 15.2% of land parcels ($n = 30$) increased in flooded wetland area over time, 79.3% ($n = 157$) did not have a detectable trend over time, and 5.6% of parcels ($n = 11$) decreased over time (Figure 8). Of the parcels where flooded wetland area increased over the years in the spring, 50.0% also increased in summer, whereas the remaining parcels showed no detectable trend in the summer. Of the parcels where flooded wetland area decreased over the years in spring, 36.4% also decreased in summer, whereas the rest showed no detectable trend in summer. Of the seven identified regions within Suisun Marsh (Figure A2B), flooded wetland area in spring increased over time in zones 2, 4, and 5 ($R^2 \geq 0.15$, $p \leq 0.039$) but did not change over time for regions 1, 3, 6, and 7 ($R^2 \leq 0.09$, $p \geq 0.12$). During the summer, flooded wetland area increased over time in regions 3, 4, 5, and 6 ($R^2 \geq 0.12$, $p \leq 0.05$) but did not change over time for regions 1, 2, and 7 ($R^2 \leq 0.06$, $p \geq 0.18$).

Correlations Between Spring and Summer Wetland Area

Flooded wetland availability for breeding waterfowl was positively correlated between spring and summer of the same year, although stronger intra-year correlations were observed at the three smaller spatial extents ($R^2 \geq 0.55$, $p < 0.001$) than at the larger extent of Suisun Marsh ($R^2 = 0.42$, $p < 0.001$), where summer-flooded wetland area increased 0.41 km^2 for every 1 km^2 increase in spring-flooded wetland area. The area of flooded wetlands in summer was positively correlated with flooded wetland area in the spring on Grizzly Island ($R^2 = 0.75$, $p < 0.001$), around the primary upland nesting area on Grizzly Island ($R^2 = 0.55$, $p < 0.001$), and around the core upland nesting area on Grizzly Island ($R^2 = 0.56$, $p < 0.001$).

Consistency of Wetlands on Individual Land Parcels

We examined the percent of land parcels that held different minimum amounts of water by establishing two different thresholds, and examined the consistency of each area threshold. Based on a threshold of ≥ 0.01 km^2 of flooded wetland area (1 hectare; 2.5 acres) per parcel, 43% of land parcels in the spring were flooded ≥90% of years, whereas 82% of land parcels were flooded ≥50% of years (Figure 8). During the summer, 28% of land parcels were flooded with ≥ 0.01 km^2 of wetland area ≥90% of years, whereas 62% of land

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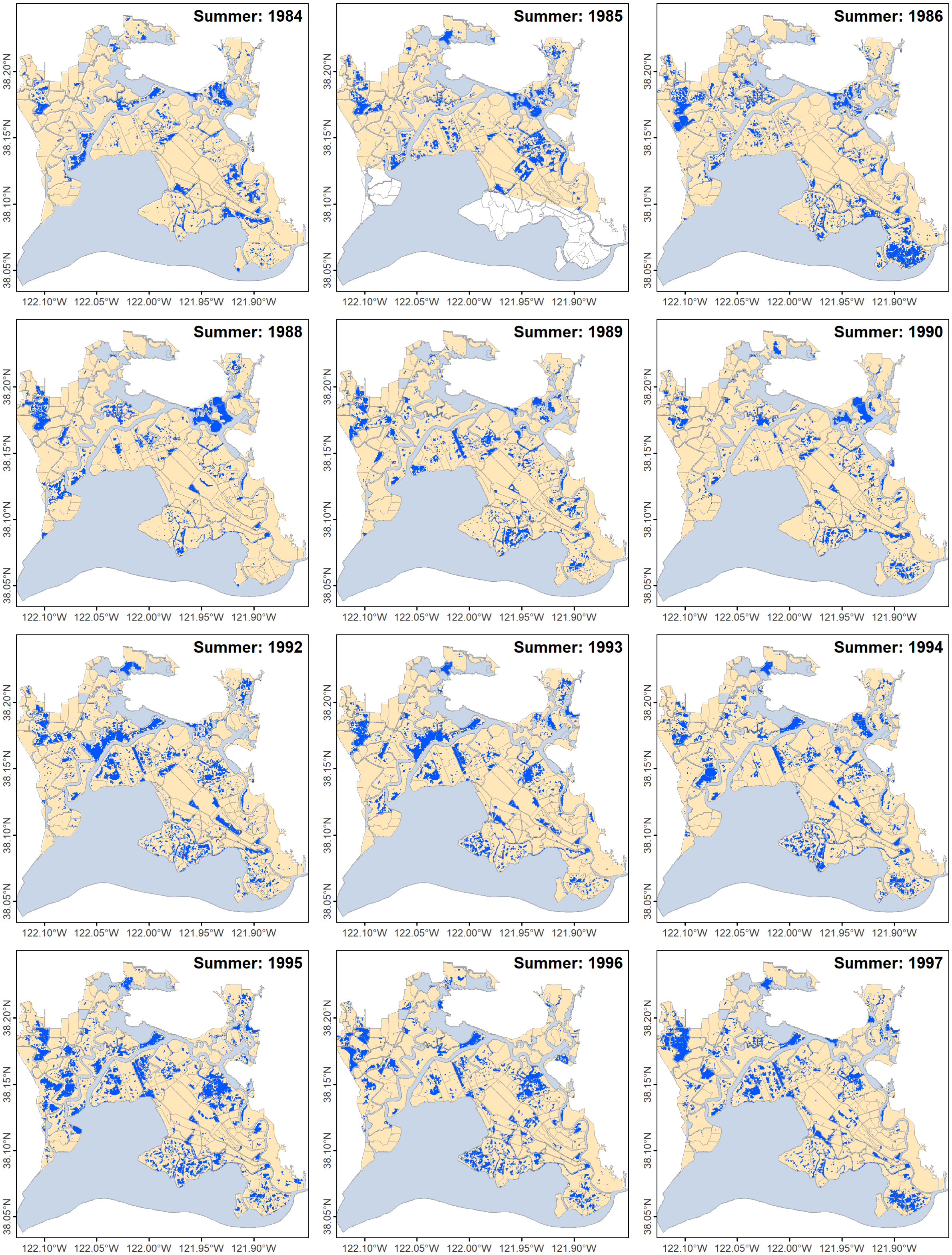

Summer: 1984

Summer: 1985

Summer: 1986

Summer: 1988

Summer: 1989

Summer: 1990

Summer: 1992

Summer: 1993

Summer: 1994

Summer: 1995

Summer: 1996

Summer: 1997

Figure 3 Maps of flooded wetland area (shown in *blue*) in the summer (composite of satellite imagery from June 17 through July 7) of each year from 1984 to 1997 (Suisun Marsh). Maps for 1987 and 1991 are not shown because a composite image could not be generated due to cloud cover interference during those years. The composite image for 1985 was excluded from statistical analyses due to > 5% missing data (indicated as *white* within Suisun Marsh) but is shown here for reference. Annual maps for the spring time frame are available in Appendix A, Figures A3 through A5.

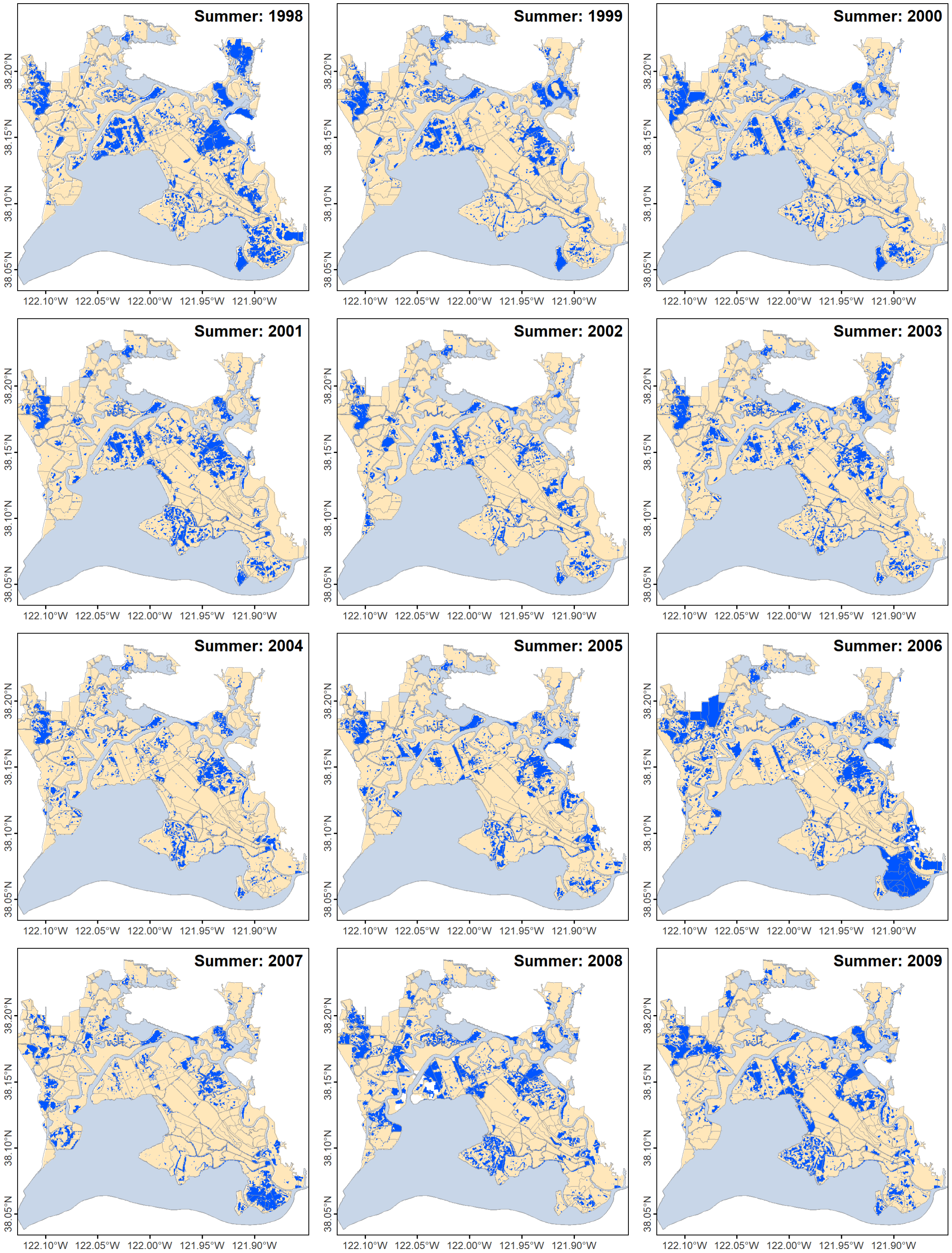

Figure 4 Maps of flooded wetland area (shown in *blue*) in the summer (composite of satellite imagery from June 17 through July 7) of each year from 1998 to 2009 (Suisun Marsh).

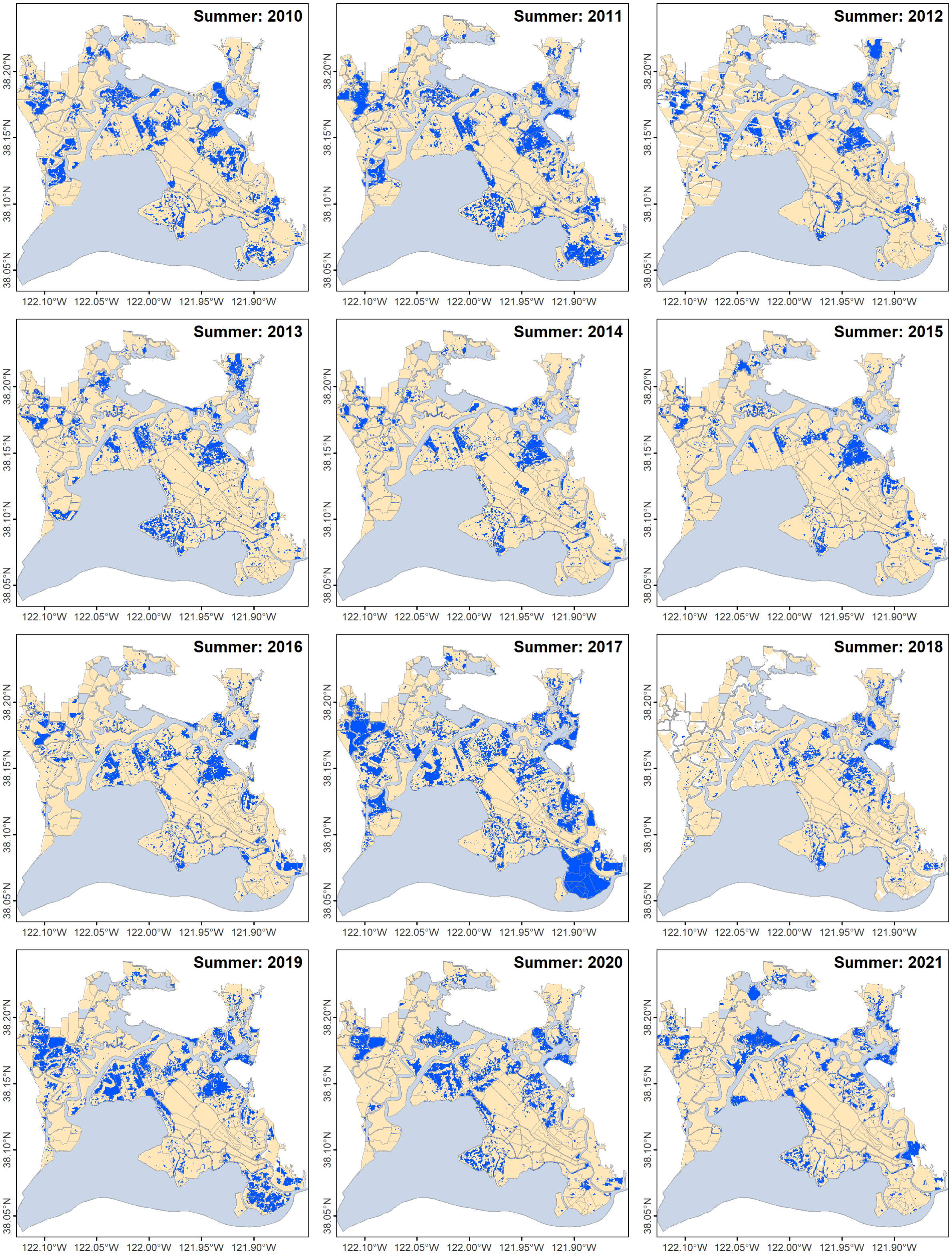

Figure 5 Maps of flooded wetland area (shown in *blue*) in the summer (composite of satellite imagery from June 17 through July 7) of each year from 2010 to 2021 (Suisun Marsh). The composite image for 2018 was excluded from statistical analyses due to > 5% missing data (indicated as *white* within Suisun Marsh) but is shown here for reference.

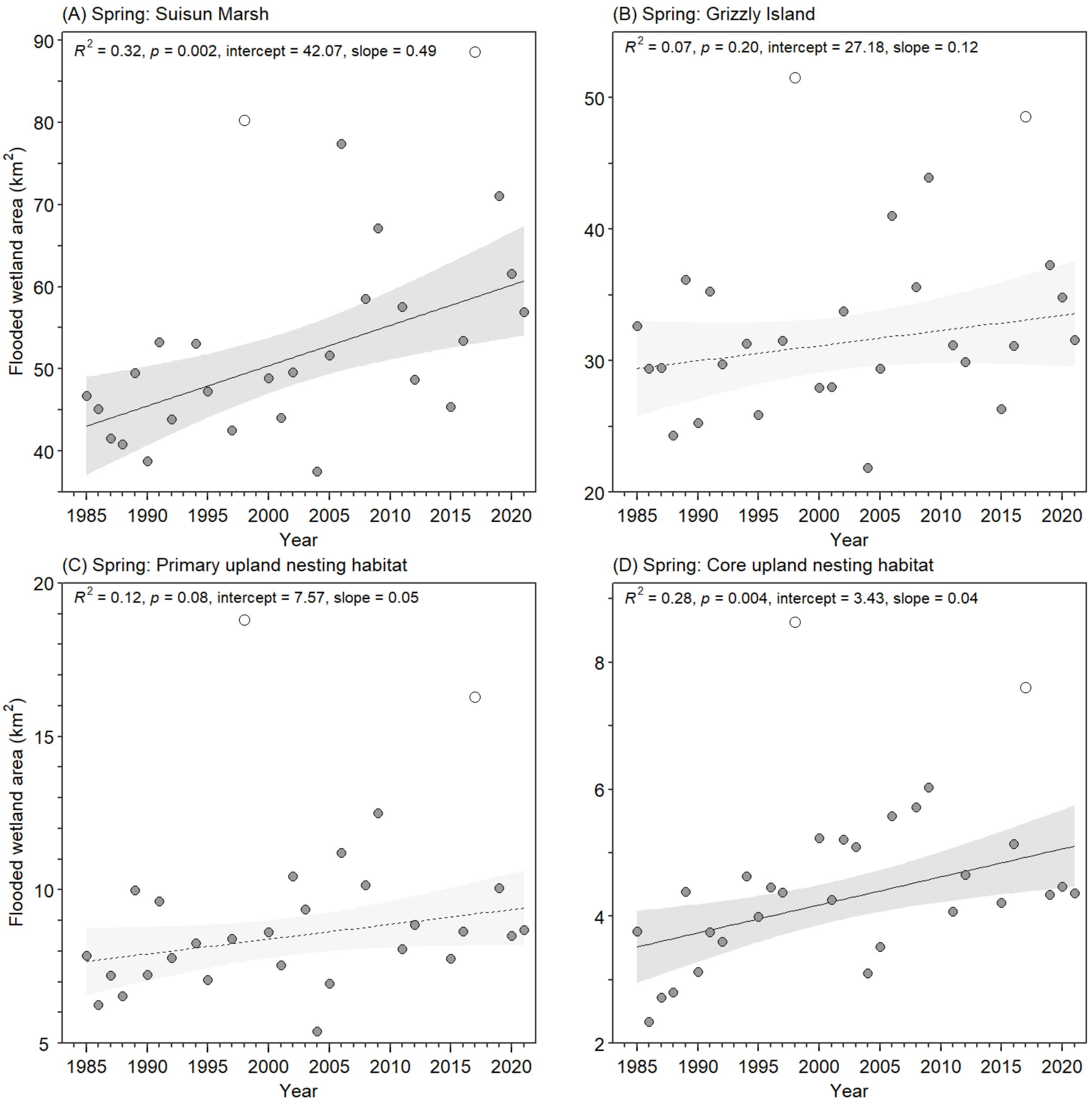

Figure 6 Flooded wetland area in the spring (composite of satellite imagery from April 27 through May 17) over time at four spatial extents in Suisun Marsh: (**A**) Suisun Marsh, (**B**) Grizzly Island, (**C**) the primary upland nesting habitat on Grizzly Island with a 1-km buffer, and (**D**) the core upland nesting habitat on Grizzly Island with a 1-km buffer. *Solid regression lines* with the 95% confidence limits are drawn for the significant linear temporal trends and *dashed lines* are shown for the non-significant linear temporal trends. Note that the *y*-axis scale differs for all spatial extents. The years 1998 and 2017 (shown as *white circles*) were excluded from statistical analyses due to levee failures and widespread unintentional flooding.

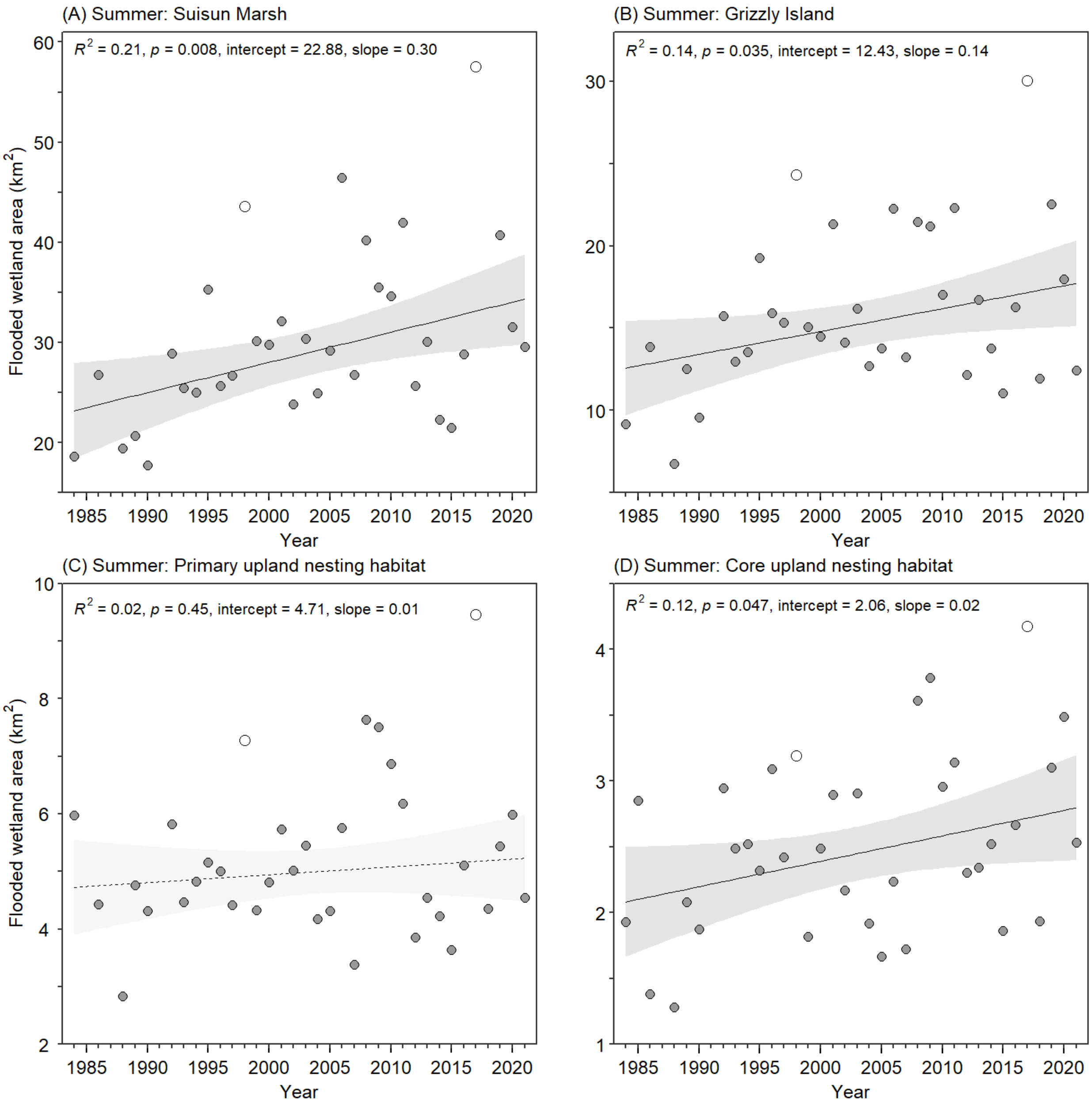

Figure 7 Flooded wetland area in the summer (composite of satellite imagery from June 17 through July 7) over time at four spatial extents in Suisun Marsh: (**A**) Suisun Marsh, (**B**) Grizzly Island, (**C**) the primary upland nesting habitat on Grizzly Island with a 1-km buffer, and (**D**) the core upland nesting habitat on Grizzly Island with a 1-km buffer. *Solid regression lines* with the 95% confidence limits are drawn for the significant temporal trends and *dashed lines* are shown for the non-significant temporal trends. Note that the *y*-axis scale differs for all spatial extents. The years 1998 and 2017 (shown as *white circles*) were excluded from statistical analyses due to levee failures and widespread unintentional flooding.

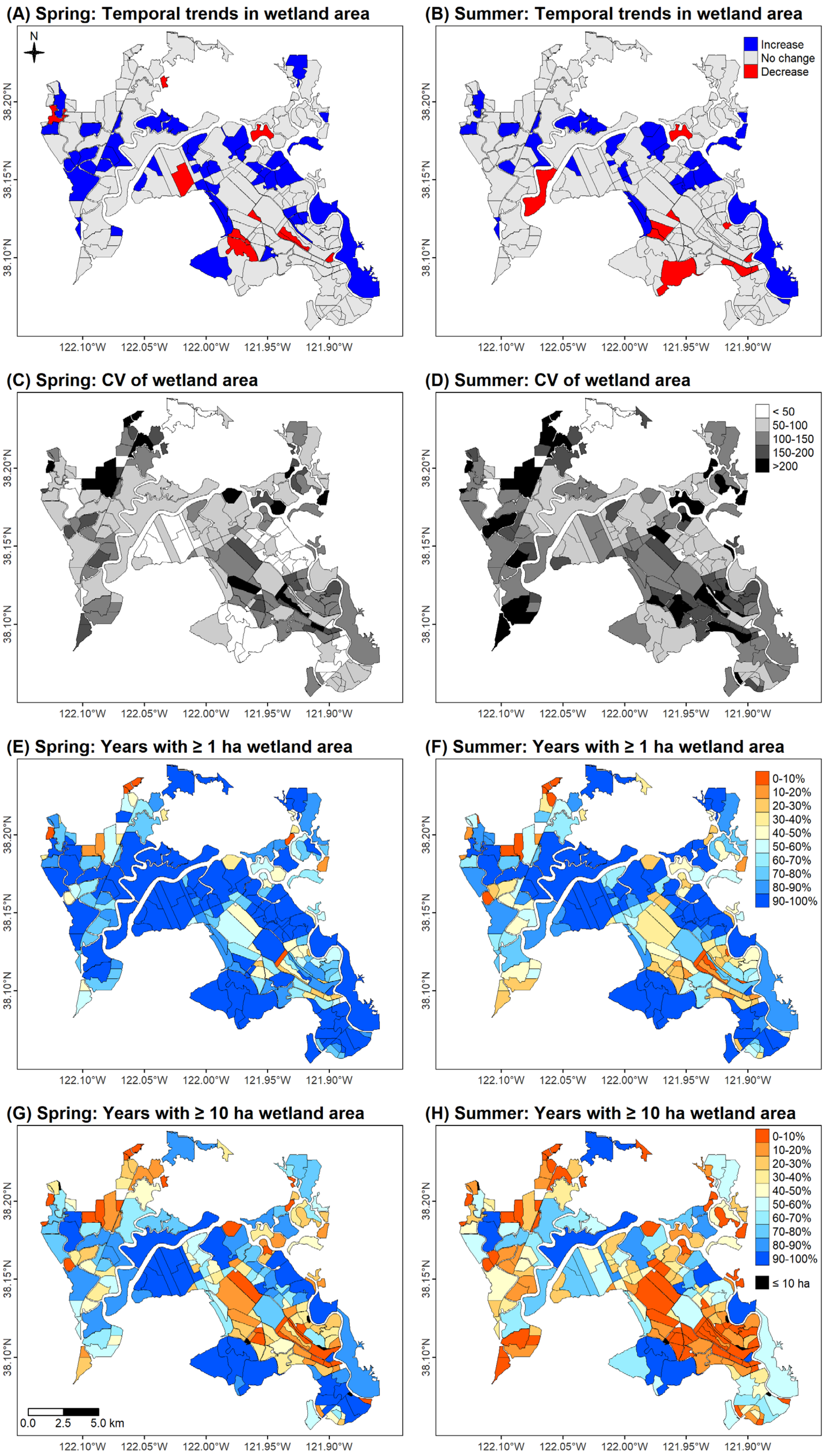

Figure 8 Temporal trends in spring and summer flooded wetland area examined for 198 private and public land parcels during (**A**) spring (composite of satellite imagery from April 27 through May 17) and (**B**) summer (composite of satellite imagery from June 17–July 7) over a 38-year period from 1984 to 2021 in Suisun Marsh, California, USA. Significant trends were identified ($p \leq 0.05$) from linear regressions done on each individual land parcel. The coefficient of variation (CV) of water availability during (**C**) spring and (**D**) summer calculated for each of the land parcels. The percentage of land parcels over the study period with ≥ 1 ha (0.01 km^2) of water during (**E**) spring and (**F**) summer. The percentage of land parcels over the study period with ≥ 10 ha (0.1 km^2) of water during (**G**) spring and (**H**) summer. Land parcels ≤ 10 ha in size are shown in *black* in panels **G** and **H**.

parcels were flooded ≥50% of years (Figure 8). Based on a threshold of 0.1 km^2 of wetland area (10 hectares; 25 acres), 16% of land parcels in the spring were flooded ≥90% of years, whereas 48% of land parcels were flooded ≥50% of years (Figure 8). During the summer, 8% of land parcels were flooded with ≥0.1 km^2 of wetland area ≥ 90% of years, whereas 28% of land parcels were flooded ≥50% of years (Figure 8).

Precipitation

Over the 38-year period, annual precipitation (October 1–April 30), including the water years of 1998 and 2017, ranged from 24.8 to 109.7 cm (58.1 ± 21.0 cm; mean ± SD), with a CV of 36.2. The two driest water years were 2020 and 2021, each with <28 cm of rain (48% of the mean annual precipitation). During the three wettest years (water years 1998, 2006, and 2017), >95 cm of rain occurred (164% of the mean). Spring precipitation (January 1–April 30), including 1998 and 2017, ranged from 8.1 to 82.2 cm (35.6 ± 17.7 cm), with a CV of 49.8. There was no detectable temporal trend in the annual or spring precipitation over the 38-year period (annual: $R^2 < 0.01$, $p = 0.86$; spring: $R^2 < 0.01$, $p = 0.88$; Figure A6).

The increase in wetland area over time during the spring did not appear to be caused by the amount of annual precipitation nor spring precipitation. Flooded wetland area in the spring, excluding water years 1998 and 2017, was not correlated with annual precipitation at any of the four spatial extents ($R^2 \leq 0.10$, $p \geq 0.12$), despite a more than 4-fold range in annual precipitation between the minimum (24.8 cm) and maximum (103.7 cm) precipitation recorded during the 38-year study period (Figure A7). Similarly, flooded wetland area in the spring was not related to spring precipitation at any of the four spatial extents ($R^2 \leq 0.07$, $p \geq 0.18$). In contrast, flooded wetland area in the summer had a weak positive correlation with the annual precipitation for the largest spatial extents, Suisun Marsh ($R^2 = 0.20$, $p = 0.01$) and Grizzly Island ($R^2 = 0.16$, $p = 0.02$), but not at the two smaller spatial extents around the upland nesting fields on Grizzly Island ($R^2 \leq 0.03$, $p \geq 0.31$; Figure 9). Similarly, the flooded wetland area in the summer had a weak positive correlation with the spring precipitation for the largest spatial extents, Suisun Marsh ($R^2 = 0.20$, $p = 0.01$) and Grizzly Island ($R^2 = 0.17$, $p = 0.02$), but not at the two smaller spatial extents around the nesting fields on Grizzly Island ($R^2 \leq 0.03$, $p \geq 0.32$).

Delta Outflow

Over the 38-year study period, annual median daily Delta outflow between March 15 and June 15 ranged from 4.3 to 98.1 kcfs (23.9 ± 26.0 kcfs; mean ± SD). There was no detectable temporal trend in the median spring Delta outflow over the 38-year period ($R^2 = 0.04$, $p = 0.25$; Figure A8). Although neither precipitation nor Delta outflow had any temporal trends from 1984 to 2021, spring Delta outflow was strongly and positively correlated with annual precipitation at the Fairfield and Napa weather stations ($R^2 = 0.71$, $p < 0.001$), including water years 1998 and 2017. Flooded wetland area in the spring for the entirety of Suisun Marsh increased with spring Delta outflow ($R^2 = 0.27$, $p = 0.007$; Figure 10), although wetland area within the smaller spatial extents was not correlated with Delta outflows ($R^2 \leq 0.04$, p ≥ 0.35). Flooded wetland area during the summer was positively correlated with spring Delta outflow at the scale of Suisun Marsh ($R^2 = 0.42$, $p < 0.001$; Figure 10) as well as Grizzly Island ($R^2 = 0.29$, $p = 0.001$), although there were no correlations between wetland area and Delta outflow at the smaller two spatial extents ($R^2 \leq 0.03$, $p \geq 0.34$). Overall flooded wetland area in Suisun Marsh did not differ among water year hydrological classifications during either the spring ($F_{4,21} = 0.74$, $p = 0.57$) or summer ($F_{4,21} = 1.09$, = 0.38; Figure 11).

DISCUSSION

In California, where more than 91% of the original wetland area has been lost, Suisun Marsh continues to provide critical wetland habitat for a variety of species, including waterbirds, mammals, and reptiles (Smith and Kelt 2019; Agha et al. 2020; Peterson et al. 2021; Schacter et al. 2021). In Suisun Marsh, we showed that the flooded wetland area available for breeding waterfowl has increased 43% in the spring (during peak nesting) and 48% in the summer (during

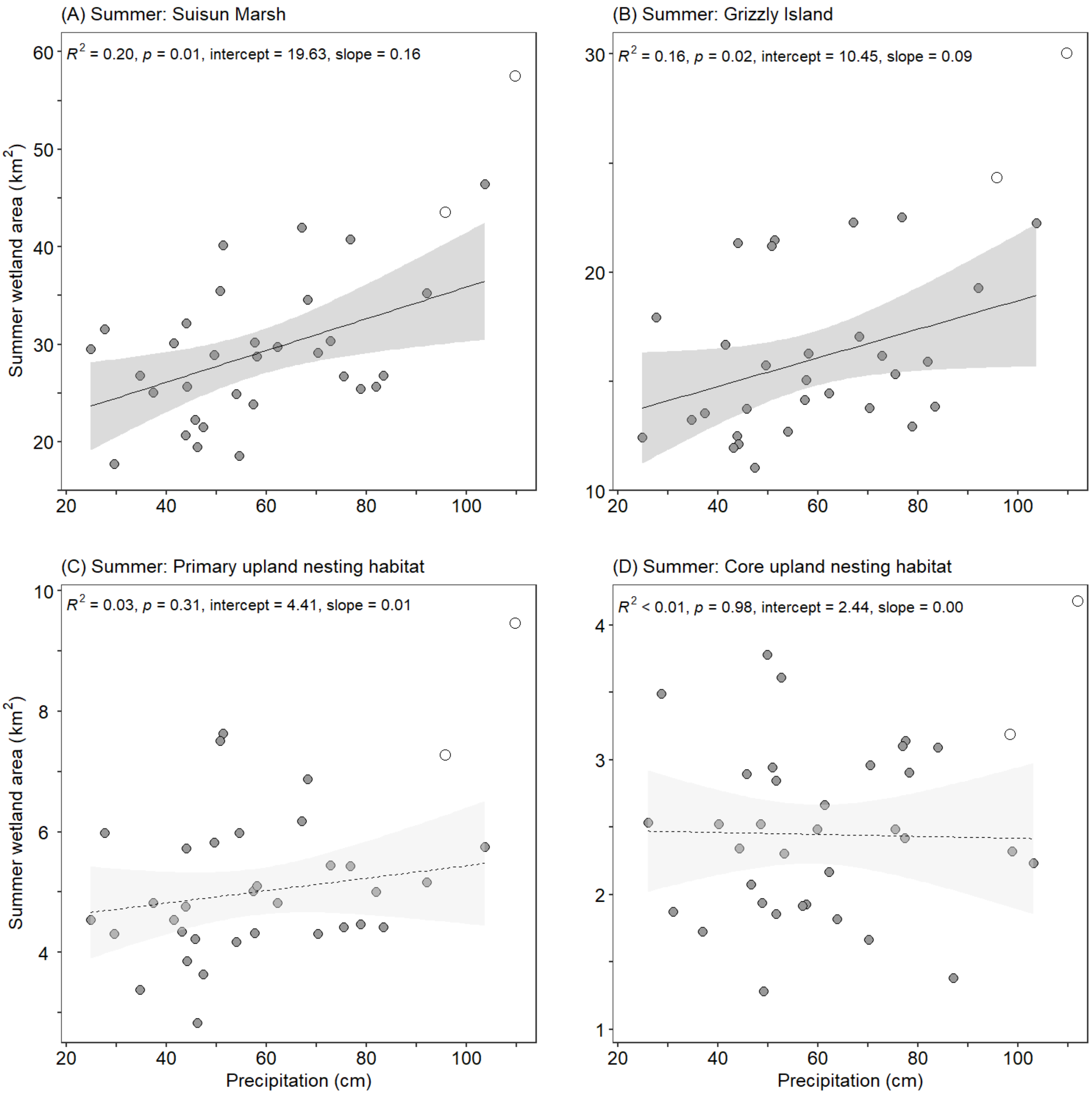

Figure 9 Flooded wetland area in summer (composite of satellite imagery from June 17 through July 7) in relation to annual precipitation (October 1 through April 30) at multiple spatial extents in Suisun Marsh: (**A**) Suisun Marsh, (**B**) Grizzly Island, (**C**) the primary upland nesting habitat on Grizzly Island with a 1-km buffer, and (**D**) the core upland nesting habitat on Grizzly Island with a 1-km buffer. *Dashed regression lines* with the 95% confidence limits are shown for the non-significant temporal trends. Water years 1998 and 2017 (shown as *white circles*) were excluded from statistical analyses due to widespread levee failures and unintentional flooding.

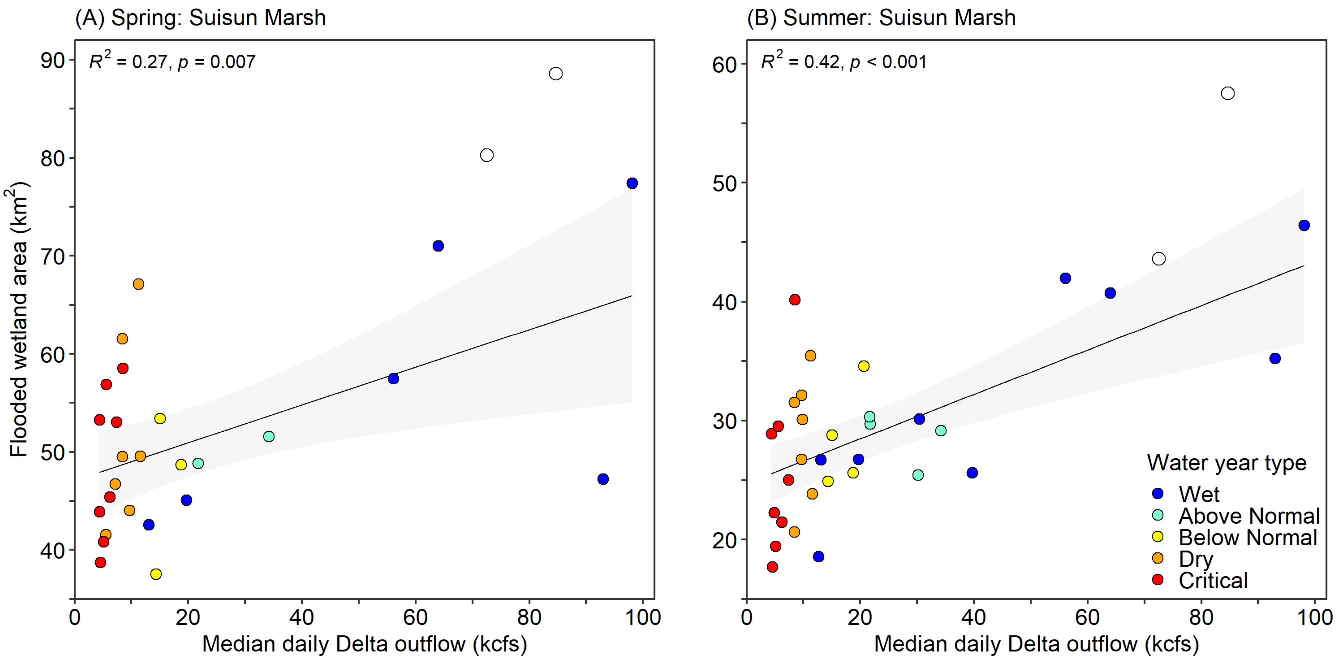

Figure 10 Flooded wetland area in Suisun Marsh in the (**A**) spring (composite of satellite imagery from April 27–May 17) and (**B**) summer (composite of satellite imagery from June 17–July 7) in relation to median daily Sacramento-San Joaquin River Delta outflow (kcfs: 1000 cubic feet of water per second) between March 15 and June 15. Water years 1998 and 2017 (shown as *white circles*) were excluded from statistical analyses due to widespread levee failures and unintentional flooding that was not due to wetland management activities. Delta outflow is color coded by the hydrological category (water year type) for the associated water year assigned to the Sacramento Valley by the California Department of Water Resources.

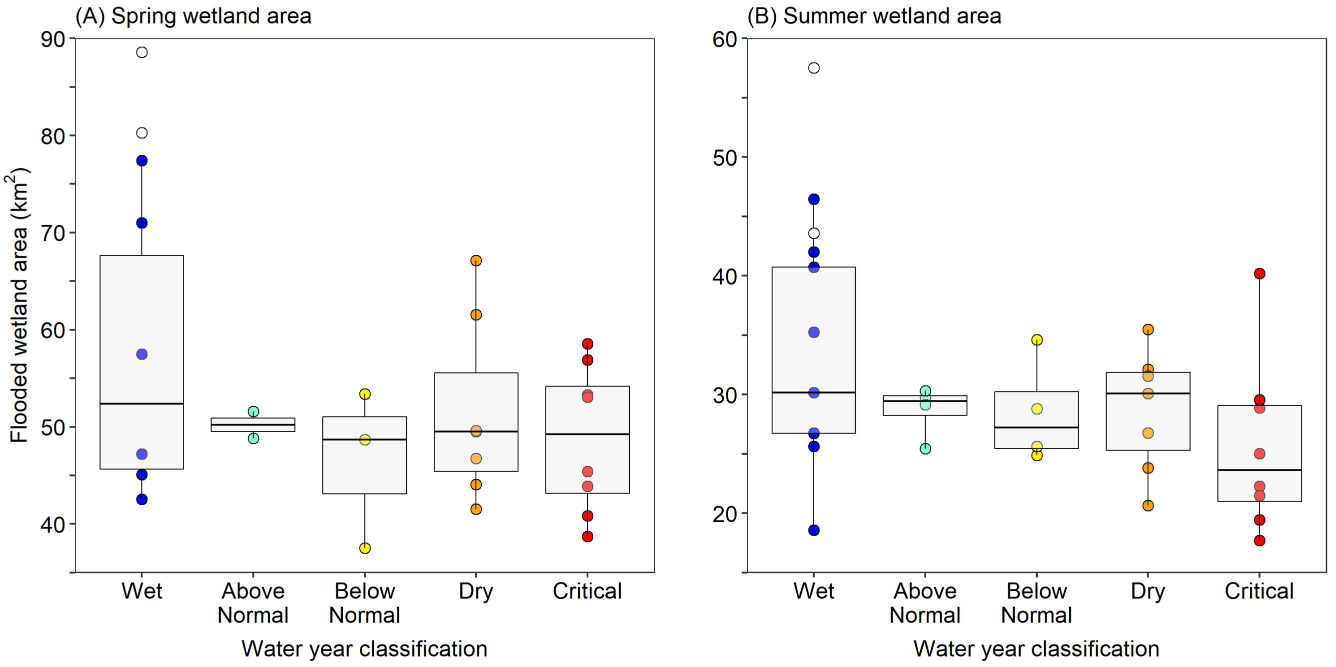

Figure 11 Flooded wetland area in Suisun Marsh during the (**A**) spring (composite of satellite imagery from April 27–May 17) and (**B**) summer (composite of satellite imagery from June 17–July 7) did not differ among hydrological categories (water year type) for the associated water year assigned to the Sacramento Valley by the California Department of Water Resources. Data are shown using boxplots, with the *box* delineating the interquartile range, the *horizontal line* showing the median value, and *whiskers* representing the full range of data. Water years 1998 and 2017 (shown as *white circles*) were excluded from statistical analyses due to widespread levee failures and unintentional flooding that was not due to wetland management activities.

peak duckling brood rearing) over the 38-year period from 1984 to 2021; however, flooded wetland area varied among years, with a 2.1-fold and 2.6-fold range during the spring and summer, respectively. Upland habitats, particularly within the Grizzly Island Wildlife Area, contain high nesting densities of dabbling duck hens (McLandress et al. 1996; Ackerman et al. 2014) that move from their nests in upland habitat to adjacent wetlands once the eggs hatch (Mauser et al. 1994; Chouinard and Arnold 2007; Casazza et al. 2020; Casazza et al. 2021). Flooded wetland area increased by 47% in spring and 34% in summer around the core upland nesting habitat on and immediately adjacent to the Grizzly Island Wildlife Area, although the flooded wetland area at this spatial scale varied up to 2.6-fold (spring) and 2.9-fold (summer) among years. Despite the overall increase in the average flooded wetland area over this 38-year period at multiple spatial scales, the among-year variability in flooded wetland area demonstrated a lack of consistency in how much flooded wetland habitat existed for breeding waterfowl each year. Of note, semi-permanent wetlands that remain flooded until at least late summer are particularly important during brood rearing (Dzus and Clark 1997; Krapu et al. 2006) but our analysis did not distinguish between permanent, semi-permanent, and seasonal wetland types. Thus, it is unknown whether the increase in wetland area was similar among wetland types.

The increase in flooded wetland area in Suisun Marsh during the spring and summer waterfowl breeding season corresponded to a period of infrastructure upgrades designed to improve the movement of water as well as wetland incentive programs that encouraged private landowners to keep wetlands flooded for longer into the waterfowl breeding season. Infrastructure improvements by the Suisun Resource Conservation District and landowners have improved managers' ability to take advantage of lower-salinity water, when available, to leach salts from wetland soils in the spring and then reflood wetlands to hold water during the summer for ducklings. Semi-permanent wetlands that hold water through August 1 are particularly important during the brood rearing period, and were selected by dabbling ducklings, whereas permanent bodies of water were avoided by dabbling ducklings. (Peterson et al. forthcoming). Although water in Suisun Marsh is consistently available to landowners through a network of brackish sloughs, the feasibility of accessing water to drain and irrigate wetlands can be constrained by (1) salinity requirements at certain times of year, (2) the gravity flow of water, and (3) water height in sloughs that can be influenced by tidal flow, Delta outflow, wind, and interactions among these environmental factors. The median daily Delta outflow in the spring was strongly correlated with annual precipitation at the Fairfield and Napa weather stations. Although excess precipitation or the net outflow of water from the Sacramento–San Joaquin River Delta may affect the ability of landowners to access water for managed wetlands, precipitation and Delta outflows did not increase over the same 38-year period, and instead either demonstrated no temporal trend or may have even decreased (Hutton et al. 2017a; Figures A6 and A8). Thus, although precipitation and Delta outflow may affect the ability to drain or re-flood managed wetlands, it is unlikely that precipitation or Delta outflows were primarily responsible for the increase in flooded wetland area in Suisun Marsh over time.

Although the net outflow of freshwater from the Sacramento–San Joaquin River Delta did not increase over time, Delta outflows in the spring varied among years (Hutton et al. 2017a; Figure A8). We observed positive correlations between flooded wetland area in Suisun Marsh and Delta outflows, although only at the largest spatial extents and not at the two smallest spatial extents (for flooded wetlands within a 1-km buffer of the primary and core upland nesting habitat on Grizzly Island). The location of the X2 zone (the location where the bottom salinity is 2 ppt) within the San Francisco Estuary differs among water year classifications (e.g., wet, dry, critical), with the X2 zone often located farthest downstream during wet water year classifications, and farthest upstream in critical water year classifications (Hutton et al.

2016, 2017b). During wetter years and periods of time with more freshwater flowing through the upper San Francisco Estuary (higher daily Delta outflow) salinity concentrations can decrease in Suisun Marsh (Beakes et al. 2021), which may make it easier for wetland management practices that retain flooded wetlands through the spring and summer waterfowl breeding season. In contrast, salinity concentrations during the spring in the San Francisco Estuary typically increase with decreasing Delta outflow (Hutton et al. 2017b). Consequently, if salinity concentrations start trending higher in Suisun Marsh and lower-salinity water is not easily accessible for wetland managers to re-flood wetlands, landowners may decide not to hold water for as long a period of time in winter-flooded wetlands or not to re-flood wetlands after their spring leach cycles have been completed. Notably, the overall flooded wetland area in Suisun Marsh did not differ between the wettest (wet) and driest (critical) water year classifications (Figure 11), as determined by the CDWR, corroborating prior research that also did not detect any relationships between water in Suisun Marsh and drought conditions (Reiter et al. 2015), and providing additional evidence that intentional management decisions determine the amount of flooded wetland habitats in Suisun Marsh during the critical spring and summer waterfowl breeding season.

Water-management actions taken in the spring after the end of the winter waterfowl hunting season can affect the availability of flooded wetlands later in the waterfowl breeding season. Although the flooded wetland area during the spring was unrelated to annual precipitation, flooded wetland area at the scale of Suisun Marsh was weakly correlated with spring Delta outflows. In contrast, during the summer, there was a positive relationship between flooded wetland area and annual precipitation at some scales, and there was a moderate relationship with spring Delta outflows. It is possible that more fall- and winter-flooded seasonal wetlands retain water for longer into the waterfowl breeding season during years with more precipitation or higher spring Delta outflows, because increased flows can provide conditions that improve managers' access to water in the late winter and early spring for multiple wetland soil leach cycles. During this 38-year study period, there was a more than 4-fold range in the annual minimum (25 cm) and maximum (104 cm) precipitation observed, which could have contributed to some wetlands taking longer to dry out in the spring after leached wetlands were reflooded or land managers actively choosing to reflood some wetlands and hold water for longer during years with more precipitation or higher Delta outflows. However, none of the relationships between flooded wetland area and environmental conditions were particularly strong, and were mostly present only at the largest spatial scale of Suisun Marsh. This underscores the complexities of managing wetlands in a brackish marsh, where the soil leach cycles that occur after the end of the annual waterfowl hunting season are critical to reduce the salt load in sediments, and the subsequent reflooding of wetlands must balance interacting environmental conditions and infrastructure constraints that influence the ability to access water, competing ecological needs of the wetlands (e.g., moist soil management for vegetation vs. retaining winter-flooded wetlands into the summer for breeding waterfowl), and maintenance requirements of the wetlands and surrounding levees. Importantly, at the two spatial scales that are likely the most critical for nesting and rearing ducklings (near to the managed upland nesting fields), we did not observe any relationships between flooded wetland area and Delta outflow. Thus, at those spatial scales, local management decisions to reflood and keep wetlands flooded during the waterfowl breeding season drove wetland availability.

Despite an overall increase in flooded wetland area over the 38-year study period, the land parcels where those increases occurred (24% of land parcels in spring and 15% in summer) were not evenly distributed throughout Suisun Marsh, suggesting that changes in the management of wetlands throughout the marsh had a spatial component and may have differed among public and private land parcels. During the summer, 23% of the parcels that increased in flooded area were in the northwest region of the marsh (region 2) and 37% were located in the central marsh (region 6; Figure A2B). In contrast, 55% of the land parcels that decreased in flooded wetland area during the summer occurred in the southern portion (region 7), including five management units within the Grizzly Island Wildlife Area, and a publicly managed parcel in region 5 which was originally intended to serve as a brood pond for waterfowl that nest in the core upland habitat on the Grizzly Island Wildlife Area (Unit 14 brood pond; Figure A9). Within 1 km of the primary upland nesting habitat on Grizzly Island, flooded wetland area in the summer increased on only two public land parcels (one was a land acquisition by the CDFW in 2018) and decreased on eight public land parcels, which could negatively affect brood-rearing waterfowl by causing ducklings to travel farther from their nest to reach wetlands and decrease the likelihood of ducklings surviving that initial movement to flooded wetland habitat (Peterson et al. 2024a). In contrast, flooded wetland area in the summer increased on seven private land parcels and did not decrease on any private land parcels, suggesting that there may have been different management strategies applied over time to the public vs. private land parcels. Only regions 4 and 5 within Suisun Marsh (Figure A2B) increased in flooded wetland area during both the spring and summer. Region 5 contains the primary upland nesting habitat available in Suisun Marsh, for both public and private land.

Our methods to quantify flooded wetland area over 4 decades have applicability for other historical imagery of wetland habitats with similar vegetation structure. Suisun Marsh wetland habitats differ from many wetlands in the California Central Valley, where spectral mixture analyses using Google Earth Engine algorithms were previously applied, and surface water was identified using a Landsat imagery pixel threshold of 0.15 (Donnelly et al. 2022) or a different analytical technique was used and a Landsat imagery pixel threshold of 0.27 was applied (Reiter et al. 2015), compared to our use of a threshold of 0.40. Our validation procedure used previously identified wetlands based on finer-resolution spectral imagery and ground-truthing of wetland boundaries (Schacter et al. 2021). Although we were only able to conduct this validation for imagery from Landsat 8 (2013–2021) and not for Landsat 5 (1984–2011) or Landsat 7 (2012), we did not observe a substantive change in flooded wetland area concurrent with a switch in satellites. From this validation procedure, we selected 0.40 as the pixel threshold to identify wetlands available for breeding waterfowl, which we felt was more conservative because waterfowl prefer wetland water depths > 15 cm (Colwell and Taft 2000; Isola et al. 2000; Peterson et al. 2024b). Our more conservative selection of the pixel threshold reduced the likelihood of falsely identifying wet mud and very shallow receding water as available wetland habitat for breeding waterfowl. If the target bird guild were shorebirds, which prefer shallower water (often < 10 cm; Dybala et al. 2017; Peterson et al. 2024b), using a lower pixel threshold would be more appropriate (Donnelly et al. 2022).

Breeding waterfowl rely on flooded wetlands during the spring and summer, and decreased availability of wetlands during the breeding season can reduce nesting effort and brood survival (Cowardin et al. 1985; Rotella and Ratti 1992; Hoekman et al. 2004; Garrick et al. 2017). Wetland habitats may be managed to prioritize production of food resources for migrating and wintering waterfowl, which may not be effective at providing flooded wetland habitat and food resources for waterfowl hens and ducklings during the breeding season. Elsewhere, particularly in the prairie pothole region, waterfowl nesting effort and population recruitment were positively correlated with spring wetland availability at large spatial scales (Cowardin et al. 1985; Johnson and Grier 1988). In California, mallard and gadwall breeding populations have declined (Ackerman et al. 2014; Brady and Weaver 2022, 2023), and the relationship between waterfowl reproduction and flooded wetland availability in California is unknown. Furthermore, the relationship between waterfowl reproduction and flooded wetland availability at smaller spatial scales may differ from patterns observed at larger geographic extents (Austin 2002). From 1984 to 2021, the flooded wetland area during peak brood rearing (summer) varied 2.6-fold among years in Suisun Marsh as a whole, and varied 2.9-fold among years for areas within 1 km of the core upland nesting habitat on Grizzly Island Wildlife Area. The lack of consistent flooded wetland habitat among years, at the time of year most important for brood rearing, could contribute to variable duckling survival rates among years (Peterson et al. 2024a) and less consistent levels of population recruitment. Changes in water-management strategies and prioritizing spring and summer waterfowl brood-rearing habitat could result in more consistent conditions among years. Water quality (e.g., salinity concentrations) and proximity to upland nesting habitats are also critical components in how beneficial wetlands are to breeding waterfowl. In Suisun Marsh, salinity concentrations vary among land parcels (Schacter et al. 2021), and some wetlands had salinity concentrations that could adversely affect ducklings (Krista et al. 1961; Schmidt–Nielsen and Kim 1964; Barnes and Nudds 1991; Moorman et al. 1991). Additionally, duckling survival can be negatively affected by the distance that waterfowl broods must travel between upland nesting habitat and nearby wetlands (Ball et al. 1975; Chouinard and Arnold 2007; Peterson et al. 2024a). Thus, understanding spring and summer wetland availability to breeding waterfowl and wetland proximity to potential upland nesting vegetation is important, and may improve the ability of resource managers to make informed decisions. Leveraging this 38-year dataset to examine specific links between wetland availability and waterfowl reproduction may be used to inform future habitat management and conservation of breeding waterfowl populations.

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REFERENCES

Ackerman JT. 2002. Of mice and mallards: positive indirect effects of coexisting prey on waterfowl nest success. Oikos. [accessed 2013 Jun 26];3:469–480. *https://doi.org/10.1034/j.1600-0706.2002.11802.x*

Ackerman JT, Eadie JM, Yarris GS, Loughman DL, McLandress MR. 2003. Cues for investment: nest desertion in response to partial clutch depredation in dabbling ducks. Anim Behav. [accessed 2013 Jun 26];66:871–883. *https://doi.org/10.1006/anbe.2003.2283*

Ackerman JT, Herzog MP, Brady C, Eadie JM, Yarris GS. 2015. Archiving California's historical duck nesting data. Open File Report 2015-1131. Dixon (CA): US Geological Survey, Western Ecological Research Center. [accessed 2025 Dec 3]. 26 p. *https://doi.org/10.3133/ofr20151131*

Ackerman JT, Herzog MP, Yarris GS, Casazza ML, Burns EW, Eadie JM. 2014. Waterfowl ecology and management. In: Moyle PB, Manfree A, Fiedler PL, editors. Suisun Marsh: ecological history and possible futures. Berkeley (CA): University of California Press. p. 103–132. Available from: *https://pubs.usgs.gov/publication/1016547*

Adams JB, Gillespie AR. 2006. Spectral-mixture analysis. In: Adams, JB, Gillespie AR, editors. Remote sensing of landscapes with spectral images: a physical modeling approach. Cambridge (UK): Cambridge University Press. p. 126–167. Available from: *https://doi.org/10.1017/CBO9780511617195*

Agha M, Yackulic CB, Riley MK, Peterson B, Todd BD. 2020. Brackish tidal marsh management and the ecology of a declining freshwater turtle. Environ Manage. [accessed 2022 Aug 10];66:644–653. *https://doi.org/10.1007/s00267-020-01326-0*

Amundson CL, Pieron MR, Arnold TW, Beaudoin LA. 2013. The effects of predator removal on mallard production and population change in northeastern North Dakota. J Wildl Manage. [accessed 2018 Sep 20];77:143–152. *https://doi.org/10.1002/jwmg.438*

Austin JE. 2002. Responses of dabbling ducks to wetland conditions in the Prairie Pothole Region. Waterbirds. [accessed 2023 Jul 18];25:465–473. Available from: *https://doi.org/10.1675/1524-4695(2002)025[0465:RODDTW]2.0.CO;2*

Ball I, Gilmer DS, Cowardin LM, Riechmann JH. 1975. Survival of wood duck and mallard broods in north-central Minnesota. J Wildl Manage. [accessed 2018 Sep 20];39:776–780. *https://doi.org/10.2307/3800241*

Barnes GG, Nudds TD. 1991. Salt tolerance in American black ducks, mallards, and their F1-hybrids. Auk. [accessed 2025 Dec 5];108:89–98. Available from: *https://www.jstor.org/stable/4088052*

Beakes MP, Graham C, Conrad JL, White JR, Koohafkan M, Durand J, Sommer T. 2021. Large-scale flow management action drives estuarine ecological response. N Am J Fish Manag. [accessed 2021 May 3];41:64–77. *https://doi.org/10.1002/nafm.10529*

Bellrose FC. 1976. Ducks, geese, and swans of North America. 3rd ed. Harrisburg (PA): Stackpole Books. 540 p. Available from: *https://www.cabidigitallibrary.org/doi/full/10.5555/19770641690*

Brady CM, Weaver M. 2022. 2022 California waterfowl breeding populations survey report. Sacramento (CA): California Department of Fish and Wildlife, Wildlife Branch/Waterfowl Program. [accessed 2023 May 31]. 17 p. Available from: *https://nrm.dfg.ca.gov/FileHandler.ashx?DocumentID=202508*

Brady CM, Weaver M. 2023. 2023 California waterfowl breeding population survey report. Sacramento (CA): California Department of Fish and Wildlife, Wildlife Branch/Waterfowl Unit. [accessed 2024 Apr 11]. 17 p. Available from: *https://nrm.dfg.ca.gov/FileHandler.ashx?DocumentID=213478*

Casazza ML, McDuie F, Jones S, Lorenz AA, Overton CT, Yee J, Feldheim CL, Ackerman JT, Thorne KM. 2021. Waterfowl use of wetland habitats informs wetland restoration designs for multi-species benefits. J Appl Ecol. [accessed 2022 Apr 10];58:1910–1920. *https://doi.org/10.1111/1365-2664.13845*

Casazza ML, Mcduie F, Lorenz AA, Keiter D, Yee J, Overton CT, Peterson SH, Feldheim CL, Ackerman JT. 2020. Good prospects: high-resolution telemetry data suggests novel brood site selection behaviour in waterfowl. Anim Behav. [accessed 2021 May 10];164:163–172. *https://doi.org/10.1016/j.anbehav.2020.04.013*

Chouinard MPJ, Arnold TW. 2007. Survival and habitat use of mallard (Anas platyrhynchos) broods in the San Joaquin Valley, California. Auk. [accessed 2018 Sep 20];124:1305–1316 *https://doi.org/10.1093/auk/124.4.1305*

Coluccy JM, Yerkes T, Simpson R, Simpson JW, Armstrong L, Davis J. 2008. Population dynamics of breeding mallards in the Great Lakes states. J Wildl Manage. [accessed 2022 Sep 13];72:1181–1187. *https://doi.org/10.2193/2007-039*

Colwell MA, Taft OW. 2000. Waterbird communities in managed wetlands of varying water depth. Waterbirds. [accessed 2022 Aug 17];23:45–55. Available from: *https://www.jstor.org/stable/4641109*

Cowardin LM, Gilmer DS, Shaiffer CW. 1985. Mallard recruitment in the agricultural environment of North Dakota. Wildl Monogr. [accessed 2018 Sep 20];92:3–37. Available from: *https://www.jstor.org/stable/3830605*

Croston R, Hartman CA, Herzog MP, Peterson SH, Kohl JD, Overton CT, Feldheim CL, Casazza ML, Ackerman JT. 2021. Interrupted incubation: how dabbling ducks respond when flushed from the nest. Ecol Evol. [accessed 2021 May 9];11:2862–2872. *https://doi.org/10.1002/ece3.7245*

[CVJV] Central Valley Joint Venture. 2020. Central Valley Joint Venture 2020 Implementation Plan. Sacramento (CA): US Fish and Wildlife Service. [accessed 2020 Jul 7]. Available from: *www.centralvalleyjointventure.org/science/2020-implementation-plan*

Dahl TE. 1990. Wetland losses in the United States: 1780s to 1980s. Washington (DC): US Department of the Interior, Fish and Wildlife Service. [accessed 2022 Jul 26]. 13 p. Available from: *https://www.fws.gov/sites/default/files/documents/Wetlands-Losses-in-the-United-States-1780s-to-1980s.pdf*

Dahl TE, Stedman S–MM. 2013. Status and trends of wetlands in the coastal watersheds of the conterminous United States 2004 to 2009. [unknown]: US Department of the Interior, Fish and Wildlife Service and National Oceanic and Atmospheric Administration, National Fisheries Service. 46 p.

Donnelly JP, Moore JN, Casazza ML, Coons SP. 2022. Functional wetland loss drives emerging risks to waterbird migration networks. Front Ecol Evol. [accessed 2022 July 25];10:1–18. *https://doi.org/10.3389/fevo.2022.844278*

Donnelly JP, Naugle DE, Collins DP, Dugger BD, Allred BW, Tack JD, Dreitz VJ. 2019. Synchronizing conservation to seasonal wetland hydrology and waterbird migration in semi-arid landscapes. Ecosphere. [accessed 2022 March 22];10:e02758. *https://doi.org/10.1002/ecs2.2758*

Dybala KE, Reiter ME, Hickey CM, Shuford WD, Strum KM, Yarris GS. 2017. A bioenergetics approach to setting conservation objectives for non-breeding shorebirds in California's Central Valley. San Franc Estuary Watershed Sci. [accessed 2018 Sep 20];15(1). *https://doi.org/10.15447/sfews.2017v15iss1art2*

Dzus EH, Clark RG. 1997. Overland travel, food abundance, and wetland use by mallards: relationships with offspring survival. Wilson Bull. [accessed 2022 Sep 20];109:504–515. [accessed 2022 Sep 20]. Available from: *https://www.jstor.org/stable/4163845*

[EROS Center] Earth Resources Observation and Science (EROS) Center. 2020a. USGS EROS Archive - Landsat Archives - Landsat 4-5 TM Collection 2 Level-2 Science Products [dataset]. US Geological Survey. [accessed 2025 Dec 3]. *https://doi.org/10.5066/P9IAXOVV*

[EROS Center] Earth Resources Observation and Science (EROS) Center. 2020b. USGS EROS Archive - Landsat Archives - Landsat 8-9 OLI/TIRS Collection 2 Level-2 Science Products [dataset]. US Geological Survey. [accessed 2022 Mar 1]. *https://doi.org/10.5066/P9OGBGM6*

[EROS Center] Earth Resources Observation and Science (EROS) Center. 2020c. USGS EROS Archive - Landsat Archives - Landsat 7 Enhanced Thematic Mapper Plus (ETM+) Level-1 Data 2 Products [dataset]. US Geological Survey. [accessed 2025 Dec 3]. *https://doi.org/10.5066/F7WH2P8G*

Garrick EJ, Amundson CL, Seddon PJ. 2017. Duckling survival of mallards in Southland, New Zealand. J Wildl Manage. [accessed 2018 Sep 20];81:858–867. *https://doi.org/10.1002/jwmg.21256*

Gorelick N, Hancher M, Dixon M, Ilyushchenko S, Thau D, Moore R. 2017. Google Earth Engine: planetary-scale geospatial analysis for everyone. Remote Sens Environ. [accessed 2022 Mar 22];202:18–27. *https://doi.org/10.1016/j.rse.2017.06.031*

Heitmeyer ME, Connelly DP, Pederson RL. 1989. The Central, Imperial, and Coachella valleys of California. In: Smith LM, Pederson RL, Kaminski RM, editors. Habitat management for migrating and wintering waterfowl in North America. [accessed 2025 Dec 3]. Lubbock (TX): Texas Tech Press. p. 475–505. Available from: *https://www.semanticscholar.org/paper/Habitat-management-for-migrating-and-wintering-in-Smith-Pederson/47cf77d766d8ca432e8af1a43ec0fe197b178473*

Hoekman ST, Gabor TS, Maher R, Murkin HR, Armstrong LM. 2004. Factors affecting survival of mallard ducklings in southern Ontario. Condor: Ornith Appl. [accessed 2022 Mar 24];106:485–495. *https://doi.org/10.1650/7408*

Hoekman ST, Mills LS, Howerter DW, Devries JH, Ball IJ. 2002. Sensitivity analyses of the life cycle of midcontinent mallards. J Wildl Manage. [accessed 2013 Aug 15];66:883–900. Available from: *http://www.jstor.org/stable/10.2307/3803153*

Hutton PH, Rath JS, Chen L, Ungs MJ, Roy SB. 2016. Nine decades of salinity observations in the San Francisco Bay and Delta: modeling and trend evaluations. J Water Resour Plan Manag. [accessed 2024 Jun 16];142:04015069. *https://doi.org/10.1061/(asce)wr.1943-5452.0000617*

Hutton PH, Rath JS, Roy SB. 2017a. Freshwater flow to the San Francisco Bay–Delta Estuary over nine decades (Part 1): trend evaluation. Hydrol Process. [accessed 2024 Mar 18];31:2500–2515. *https://doi.org/10.1002/hyp.11201*

Hutton PH, Rath JS, Roy SB. 2017b. Freshwater flow to the San Francisco Bay–Delta Estuary over nine decades. Part 2: change attribution. Hydrol Process. [accessed 2024 Mar 20];31:2516–2529. *https://doi.org/10.1002/hyp.11195*

Isola CR, Colwell MA, Taft OW, Safran RJ. 2000. Interspecific differences in habitat use of shorebirds and waterfowl foraging in managed wetlands of California's San Joaquin Valley. Waterbirds. [accessed 2022 Aug 17];23:196–203. Available from: *https://www.jstor.org/stable/4641140*

Johnson DH, Grier JW. 1988. Determinants of breeding distributions of ducks. Wildl Monogr. [accessed 2022 Aug 13];100:3–37. Available from: *https://www.jstor.org/stable/3830704*

Johnson DH, Sparling DW, Cowardin LM. 1987. A model of the productivity of the mallard duck. Ecol Modell. [accessed 2022 Jul 26];38:257–275. *https://doi.org/10.1016/0304-3800(87)90100-1*

Krapu GL, Klett AT, Jorde DG. 1983. The effect of variable spring water conditions on mallard reproduction. Auk. [accessed 2022 Feb 23];100:689–698. *https://doi.org/10.1093/auk/100.3.689*

Krapu GL, Pietz PJ, Brandt DA, Cox Jr RR. 2006. Mallard brood movements, wetland use, and duckling survival during and following a prairie drought. J Wildl Manage. [accessed 2018 Sep 23];70:1436–1444. *https://doi.org/10.2193/0022-541x(2006)70[1436:mbmwua]2.0.co;2*

Krista LM, Carlson CW, Olson OE. 1961. Some effects of saline waters on chicks, laying hens, poults, and ducklings. Poult Sci. [accessed 2020 Nov 23];40:938–944. *https://doi.org/10.3382/ps.0400938*

Manfree A. 2014. Historical ecology. In: Moyle PB, Manfree A, Fiedler PL, editors. Suisun Marsh: Ecological history and possible futures. Berkeley (CA): University of California Press. p. 9–44. [accessed 2025 Dec 5]. Available from: *https://books.google.com/books?hl=en&lr=&id=n48jAwAAQBAJ&oi=fnd&pg=PP1&dq=Moyle+PB,+Manfree+A,+Fiedler+PL,+editors.+Suisun+Marsh:+Ecological+history+and+possible+futures.&ots=q4tppcwftS&sig=eeRCOQeE3QcJl0JT6sNLAFKJbtE#v=onepage&q&f=false*

Mauser DM, Jarvis RL, Gilmer DS. 1994. Movements and habitat use of mallard broods in northeastern California. J Wildl Manage. [accessed 2018 Sep 23];58:88–94. *https://doi.org/10.2307/3809553*

McLandress MR, Yarris GS, Perkins AEH, Connelly DP, Raveling DG. 1996. Nesting biology of mallards in California. J Wildl Manage. [accessed 2018 Sep 23];60:94–107. *https://doi.org/10.2307/3802044*

Moorman AM, Moorman TE, Baldassarre GA, Richard DM. 1991. Effects of saline water on growth and survival of Mottled Duck ducklings in Louisiana. J Wildl Manage. [accessed 2020 Nov 23];55:471–476. *https://doi.org/10.2307/3808977*

Null SE, Viers JH. 2013. In bad waters: water year classification in nonstationary climates. Water Resour Res. [accessed 2024 Jun 17];49:1137–1148. *https://doi.org/10.1002/wrcr.20097*

Peterson SH, Ackerman JT, Fettig BL, Greenawalt AC, Hartman CA, Keating MP, Herzog MP. Wetland characteristics influence dabbling duckling habitat use and movements. Submitted to Ornithological Applications.

Peterson SH, Ackerman JT, Hartman CA, Casazza ML, Feldheim CL, Herzog MP. 2021. Mercury exposure in mammalian mesopredators inhabiting a brackish marsh. Environ Pollut. [accessed 2021 Jan 24];273:115808. *https://doi.org/10.1016/j.envpol.2020.115808*

Peterson SH, Ackerman JT, Hartman CA, Greenawalt AC, Casazza ML, Herzog MP. 2024a. Duckling survival increased with availability of flooded wetland habitat and decreased with salinity concentrations in a brackish marsh. Ornithol Appl. [accessed 2024 July 04];126:duae017. *https://doi.org/10.1093/ornithapp/duae017*

Peterson SH, Ackerman JT, Schacter CR, Hartman CA, Herzog MP. 2024b. Bird habitat value and management priorities of the California Winter Rice Habitat Incentive Program. San Franc Estuary Watershed Sci. [accessed 2025 Dec 5];22:(3). *https://doi.org/10.15447/sfews.2024v22iss3art3*

Peterson SH, Lorenz AA, Ackerman JT. 2025. Historical flooded wetland availability in Suisun Marsh. US Geological Survey data release. [accessed 2020 Sep 14]. Available from: *https://doi.org/10.5066/P17CCSVH*

Planet Team. 2017. Planet Application Program Interface: in space for life on earth. San Francisco (CA): Planet Labs PBC. [accessed 2025 Dec 3]. Available from: *https://api.planet.com*

R Core Team. 2024. R: a language and environmental for statistical computing. Vienna (Austria): R Foundation for Statistical Computing. [accessed 2024 May 17]. Available from: *https://www.R-project.org/*

Reiter ME, Elliott N, Veloz S, Jongsomjit D, Hickey CM, Merrifield M, Reynolds MD. 2015. Spatio-temporal patterns of open surface water in the Central Valley of California 2000–2011: drought, land cover, and waterbirds. J Am Water Resour Assoc. [accessed 2025 Dec 3];51:1722–1738. *https://doi.org/10.1111/1752-1688.12353*

Rotella JJ, Ratti JT. 1992. Mallard brood survival and wetland habitat conditions in southwestern Manitoba. J Wildl Manage. [accessed 2022 Jul 25];56:499–507. *https://doi.org/10.2307/3808865*

Schacter CR, Peterson SH, Herzog MP, Hartman CA, Casazza ML, Ackerman JT. 2021. Wetland availability and salinity concentrations for breeding waterfowl in Suisun Marsh, California. San Franc Estuary Watershed Sci. [accessed 2021 Jun 13];19:(3). *https://doi.org/10.15447/sfews.2021v19iss3art5*

Schmidt–Nielsen K, Kim YT. 1964. The effect of salt intake on the size and function of the salt gland of ducks. Auk. [accessed 2020 Nov 23];81:160–172. *https://doi.org/10.2307/4082766*

[SFEI–ASC] San Francisco Estuary Institute and Aquatic Science Center. 2017. Bay Area Aquatic Resource Inventory (BAARI) version 2.1 GIS Data. [accessed 2018 Nov 26]. Available from: *http://www.sfei.org/data/baari-version-21-gis-data*

Smith KR, Barthman–Thompson LM, Estrella SK, Riley MK, Trombley SN, Rose CA, Kelt DA. 2020. Demography of the salt marsh harvest mouse (*Reithrodontomys raviventris halicoetes*) and associated rodents in tidal and managed wetlands. J Mammal. [accessed 2020 Feb 20];129–142. *https://doi.org/10.1093/jmammal/gyz183*

Smith KR, Kelt DA. 2019. Waterfowl management and diet of the salt marsh harvest mouse. J Wildl Manage. [accessed 2022 Aug 10];83:1687–1699. *https://doi.org/10.1002/jwmg.21752*

Sommer T, Hartman R, Koller M, Koohafkan M, Conrad JL, MacWilliams M, Bever A, Burdi C, Hennessy A, Beakes M. 2020. Evaluation of a large-scale flow manipulation to the upper San Francisco Estuary: response of habitat conditions for an endangered native fish. PLOS ONE. [accessed 2022 Jul 25];15:0234673. *https://doi.org/10.1371/journal.pone.0234673*

Story M, Congalton RG. 1986. Accuracy assessment: a user's perspective. Photogramm Eng Remote Sensing. [accessed 2024 July 04];52:397–399. [accessed 2025 Dec 5]. Available from: *https://scholars.unh.edu/faculty_pubs/1247/*

[SWRCB] State Water Resources Control Board. 2018. Water quality control plan for the San Francisco Bay/Sacramento–San Joaquin Delta Estuary. Sacramento (CA): SWRCB. [accessed 2025 Jul 8]. 76 p. Available from: *https://www.google.com/url?client=internal-element-cse&cx=001779225245372747843:ttksqsdjfn4&q=https://www.waterboards.ca.gov/plans_policies/docs/2018wqcp.pdf&sa=U&ved=2ahUKEwiept29pqSRAxXnKlkFHYDkIHQQFnoECAUQAg&usg=AOvVaw29kuJdew3f3y76veohPESS*

Thorne K, MacDonald G, Guntenspergen G, Ambrose R, Buffington K, Dugger B, Freeman C, Janousek C, Brown L, Rosencranz J, et al. 2018. US Pacific coastal wetland resilience and vulnerability to sea-level rise. Sci Adv. [accessed 2022 Jul 5];4:1–11. *https://doi.org/10.1126/sciadv.aao3270*

Wilen BO, Frayer WE. 1990. Status and trends of US wetlands and deepwater habitats. For Ecol Manage. [accessed 2021 Nov 4];33–34:181–192. *https://doi.org/10.1016/0378-1127(90)90192-E*

NOTES

Chappell S. 2024a. Email exchange on August 6, 2025, between Steve Chappell, SRCD, and S. Peterson regarding the Suisun Resource Conservation District's fish screening program.

Chappell S. 2024b. In-person conversation between Steve Chappell, SRCD, and S. Peterson regarding Suisun Marsh water management.

Chappell S, Takekawa J. 2024c. Video conference with John Takekawa, SRCD, and S. Peterson on June 26, 2024, regarding Suisun Marsh water management.