Assessing shrinkage and fragmentation of Wetlands in the Sacramento-San Joaquin Delta, California from the Early 1800s to Present

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ABSTRACT

Wetlands within the Sacramento-San Joaquin Delta in California have historically been rich in biodiversity, natural resources, and ecosystem services. Since the late 1800s, conversion of wetlands to agricultural land has led to a loss of 98% of wetlands in the Delta and a subsequent loss of ecosystem services and ecological functions, including wildlife habitat. To address this, restoration projects have been undertaken in the Delta, but planning for these restorations have not focused on incorporating landscape level features necessary for system-wide functionality. I assessed landscape-level shrinkage and fragmentation of wetland habitats by calculating changes in landscape metrics (e.g., mean patch size, number of patches, and perimeter-area ratio) from the early 1800s to 2009. I assessed changes in the spatial distribution of wetlands using spatial analysis tools, such as the Average Nearest Neighbor tool. Overall there was extensive habitat shrinkage and fragmentation with a considerable decrease in mean wetland patch size (4425.46 ± 22834 ha to 4.94 ± 54 ha), increase in the number of wetland patches (55 historical patches to 2920 modern patches), and a shift in the spatial pattern of wetlands from clustered to dispersed (p-value<0.01). This project will help enhance wetland restoration management and monitoring in the Delta by providing an understanding of how the landscape has changed.

KEYWORDS

GIS, FRAGSTATS, spatial analysis, landscape-scale restoration, landscape metrics

INTRODUCTION

Wetlands provide a multitude of ecosystem services such as flood water attenuation, ground water recharge, habitat for species, water purification, and sinks for excess nutrients including carbon (Erwin 2008). Though wetlands only make up 6% of Earth's land area, they serve as a sink for 12% of global carbon, making wetlands integral to sequestering atmospheric CO_2 (Junk et al. 2012). There has been a 30-90% loss of global wetlands which has led to a loss of the key ecosystem services provided by wetlands, making them important habitats to conserve and restore (Erwin 2008).

To improve the ecological function in degraded ecosystems, large-scale restoration efforts are needed. Restorations are typically done for site-specific reasons, but this approach does not account for the loss of key ecosystem processes and structures necessary for system-wide functionality (Simenstad et al. 2006, Junk et al. 2012). Small-scale restorations are generally aimed at providing specific ecosystem services, such as increasing carbon sequestration, while large-scale restoration efforts focus on increasing habitat extent, connectivity, and physical processes necessary for ecological function (Beagle et al. 2015). Many studies have shown the need for landscape-scale restoration, but the inherent difficulty of acquiring the amount of land necessary for such a large restoration project makes it challenging to put this restoration approach into action (Beagle et al. 2015, Robinson et al. 2014). However, a fundamental first step to landscape-scale restoration is to attain a full understanding of how an ecosystem has changed over time.

The Sacramento-San Joaquin Delta, located in Northern California, is an example of a wetland network that has been severely degraded. The Sacramento-San Joaquin Delta begins in California's Central Valley (Figure 1), where the Sacramento and San Joaquin rivers converge. The Delta is approximately the size of Rhode Island, making it the largest delta on the pacific coast of North America (Luoma et al. 2015). Prior to the 1800s, the defining characteristic of the Delta was its extensive wetland network that supported a diverse wildlife community and contained half of California's estuarine wetlands (Robinson et al. 2014). Approximately 750 plant and animal species inhabit the Delta today, including bird species such as coots, ducks, and geese, that use the Delta's wetlands as protection from predators, a food source, and a resting stop during migration (Sharma et al. 2016, Robinson et. al 2014).

This ecologically important ecosystem underwent a drastic transformation in the mid-nineteenth century when many wetlands were drained and diked for agricultural use (Madani and Lund 2012). Diking and levee construction has prevented many natural processes, such as the deposition of new soil from rivers flooding into wetland habitat, from being able to occur. Flood management levees have prevented the flow of sediments, nutrients, and organisms to wetlands (Robinson et al. 2014). With 98% of the wetlands in the Delta destroyed, the Delta is no longer a connected landscape, making it increasingly difficult for species to travel between wetlands (Howe and Simenstad 2011). As a result, populations are becoming isolated and gene flow is being limited, potentially causing local extinctions (Robinson et al. 2014, Howe and Simenstad 2011).

A detailed understanding of how diking and draining Delta wetlands has changed habitat extent and connectivity can help improve restoration efforts aimed at increasing ecological function. Historical maps can help establish an understanding of what key aspects are no longer present in the current landscape and incorporation of this data into the restoration process could help to increase ecological function of the Delta. Previous studies determining how wetland distributions have changed due to human disturbances found increased mean distance between wetlands, which is known to obstruct species migration. Knowledge of how specific attributes of a landscape have changed over time helps to inform what types of restoration techniques are best suited for a site (Robinson et al. 2014). Though the extent of habitat loss is known in broad terms, a better understanding of the changes in habitat distribution, shape, size, and connectivity of specific habitats in the Delta is needed. There have been efforts to restore portions of the Delta, but these restoration efforts have not been focused on the landscape-scale.

The central aim of this study is to assess how wetland habitat extent and connectivity in the Delta have changed over time. In order to do this I will determine how key characteristics of wetlands (e.g. size, shape, number of wetland patches, etc.) have changed from the 1800s to the present. I hypothesize that modern wetland sizes have decreased and that they have a more uniform shape when compared to historical wetlands. I will then determine how the spatial distribution of wetlands in the Delta has changed. I hypothesize that modern distribution of wetlands is dispersed compared to historic wetland distribution. Using satellite data of the historic and current Delta, I will create maps using GIS technology to show how different aspects of the Delta have changed over time.

METHODS

Study site:

The Sacramento San-Joaquin Delta is the largest delta on the pacific coast of North America (Luoma et al. 2015). This delta is located in Northern California (38.13° N, 121.53° W) and once contained half of California's estuarine wetlands (Robinson et al. 2014). The Delta begins in the Central Valley where the Sacramento and San Joaquin rivers converge and collects water as it flows into the San Francisco Bay. It is approximately 2,800 km^2 with roughly 70% allocated for agricultural use (Robinson et. al 2014). Though the Delta is located in a region with a Mediterranean climate, it is a perennial freshwater source (Robinson et. al 2014). The Delta is an important freshwater source that provides irrigation water to over 7 million acres of agricultural land and drinking water for two-thirds of California's population (Burton and Cutter 2008).

Figure 1. Study Site Location. The pin indicates the location of the Sacramento-San Joaquin Delta within California and a close up of the boundary of the Delta.

Data collection and processing

The datasets used to analyze how the Delta has changed over time were obtained from the San Francisco Estuary Institute (SFEI) and the United States Fish and Wildlife Service (USFWS). The Delta Historical Ecology GIS Data map was used to represent the historic Delta (SFEI 2012). It is a vector dataset originally created as a part of the Sacramento-San Joaquin

Delta Historical Study and is a reconstruction of historical landscape of the Delta in the early 1800s. This map was created by orthorectifying historical maps and aerial photos and using historical accounts, descriptions of the Delta from newspapers, traveler accounts, survey notes, et cetera to determine specific features of the Delta. The U.S. FWS's National Wetland Inventory (NWI) is a publically available vector dataset of all wetlands in America (USFWS 2009). It includes information about distributions, characteristics, and abundance of wetlands that is used by natural resource managers. The NWI data was used to represent the modern Delta. I used ArcGIS 10.4.1 to process both datasets. I transformed the NWI and Delta Historical Ecology Data Map to the NAD 1983 Albers projection/datum. The NWI dataset was clipped to the Delta Historical Ecology GIS Data Map so the datasets represented the same spatial extent. Both datasets were converted from vector to raster format (tiff) at 30 m resolution for use in Fragstats.

Shrinkage and fragmentation analysis using landscape metrics

Landscape metrics were used identify trends in wetland shrinkage and fragmentation over time. Landscape metrics are a set of indices that quantify and characterize spatial patterns at an observed landscape (McGarigal and Marks 1995, Shrestha et al. 2012). I used Fragstats 4 to calculate five metrics for the historic and current Delta. I used Five metrics because using only one metric is not enough to properly encapsulate the spatial arrangement complexities (Riitters et al. 1995). The *mean patch size* is a commonly used metric in spatial pattern analysis (Baldi et al. 2006). The *percentage of landscape* quantifies the proportional abundance of each patch types in the landscape (McGarigal and Marks 1995). The *number of patches* metric measures the extent of fragmentation or subdivision for a patch type (McGarigal and Marks 1995). The *perimeter-area ratio* is a metric for patch shape complexity without standardization to a Euclidean shape (e.g. circle or square) (McGarigal and Marks 1995). The perimeter-area ratio is a useful metric in determining the amount of a patch that is exposed to edge effects or transition areas because it does not require a subjective estimation of how far the edge extends into a patch (Faaborg et al. 1993, Helzer and Jelinski 1999). The *Euclidean nearest-neighbor distance* quantifies the isolation of patches and is a measure of the distance between a patch of interests and its nearest neighbor patch of the same class (McGarigal and Marks 1995). Table 1 includes the formulas used to calculate each landscape metrics.

Table 1. Formulas for all calculated landscape metrics.

Mean Patch Size	$$\frac{\sum_{j=1}^{n} x_{ij}}{n_i}$$ x_{ij} = area (m^2) of the jth patch belonging to the ith patch type n_i = number of patches in the landscape of patch type i
Standard Deviation	$$\sqrt{\frac{\sum_{j=1}^{n}\left[x_{ij}-\left(\frac{\sum_{j=1}^{n} x_{ij}}{n_i}\right)\right]^2}{n_i}}$$ $_{ij}$ = jth patch belonging to the ith patch type n_i = number of patches in the landscape of patch type i
Percentage of Landscape	$$\frac{\sum_{j=1}^{n} a_{ij}}{A}(100)$$ a_{ij} = area (m^2) of the jth patch belonging to the ith patch type A = total landscape area (m^2)
Number of Patches	n_i = number of patches in the landscape of patch type i
Perimeter Area Ratio	$$\frac{p_{ij}}{a_{ij}}$$ p_{ij} = perimeter (m) of jth patch belonging to the ith patch type a_{ij} = area (m^2) of the jth patch belonging to the ith patch type
Euclidean Nearest Neighbor	h_{ij} = distance (m) from the jth patch belonging to the ith landscape to nearest neighbor patch of the same type (based on patch edge-to-edge distance, computed from cell center to cell center

Spatial analysis of shrinkage and fragmentation

To determine how the spatial distribution of wetlands in the Delta has changed over time, I used tools from ArcMap 10.4.1. Since the NWI uses a biological definition of wetland type and extent, there was no attempt made to define or establish boundaries of restored wetland (USFWS 2009). This means that wetland patches mapped in the NWI dataset did not accurately represent wetland patches at a landscape scale. I therefore used a combination of hot spot analysis and wetland polygon aggregation in order to better represent wetland habitats at the landscape level. The Optimized Hot Spot Analysis tool was used to identify areas of statistically significant spatial clustering of wetlands in the current Delta. This tool uses the Getis-Ord Gi* statistic in order to create a map of statistically significant hot and cold spots based on weights given to polygon features. Since I applied a weight of one if a polygon was classified as a wetland and a weight of zero if a polygon was anything else, a hot spot was indicative of an area with significant wetland clustering. Wetland polygons located within a hot spot cluster of wetlands with z-scores greater than 2.8 were aggregated into a single wetland hot spot polygon using the Aggregate Polygons tool.

To determine whether there was significant dispersion or clustering in the distribution of wetlands for the historic and modern Delta I used the Average Nearest Neighbor tool. This tool averages all the distances between the center of each feature and the center of its nearest neighbor. If the average distance is less than the calculated expected average distance, the distribution of features is said to be clustered.

RESULTS

Shrinkage and fragmentation analysis using landscape metrics

Over time, both wetland habitat fragmentation and shrinkage have increased. The mean wetland patch size of the historic Delta (4,425.46 ha ± 22,834 ha) is greater than the modern Delta (4.94 ha ± 54 ha) (Figure 2). The distribution of wetland habitat area is right-skewed for the modern and historic Delta probability density function, but the modern Delta has a greater right skew with wetland patches less than 1 ha having the highest probability (Figure 3). While the Euclidean nearest neighbor distances decreased from the historic to modern Delta, the current Delta has more outliers with higher nearest neighbor distances (Figure 4). Percentage of the landscape covered by wetlands decreased, while the number of wetland patches, and the perimeter area ratio increased (76.7% to 8.4%, 55 to 2920, and 502.31 to 914.07, respectively). Landscape metrics are listed in Table 2.

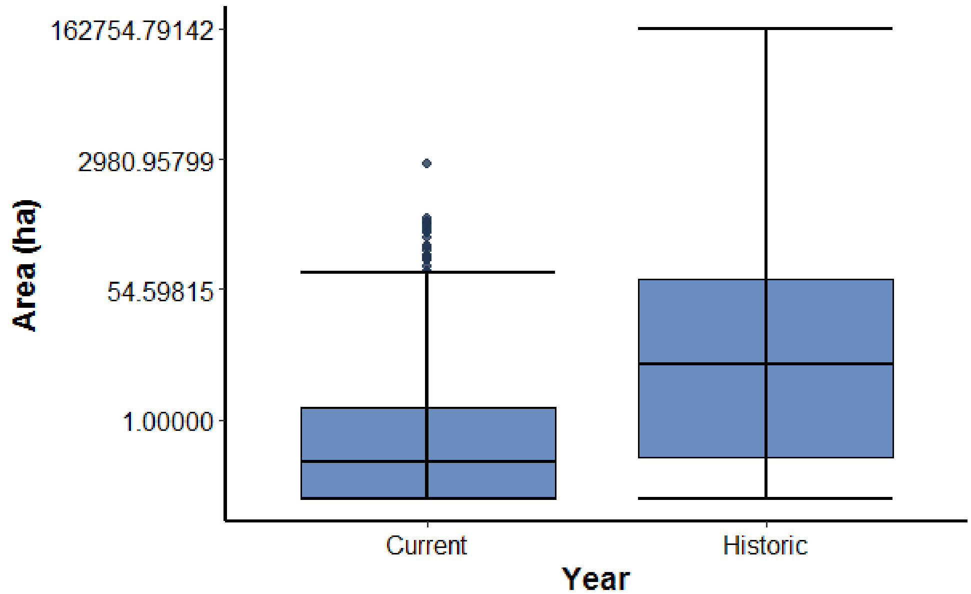

Figure 2. Change in wetland area from the historic to modern Delta. The Boxplots show a decrease in the average wetland patch size over time. The historic Delta has long whiskers indicating a wide range in wetland patch size.

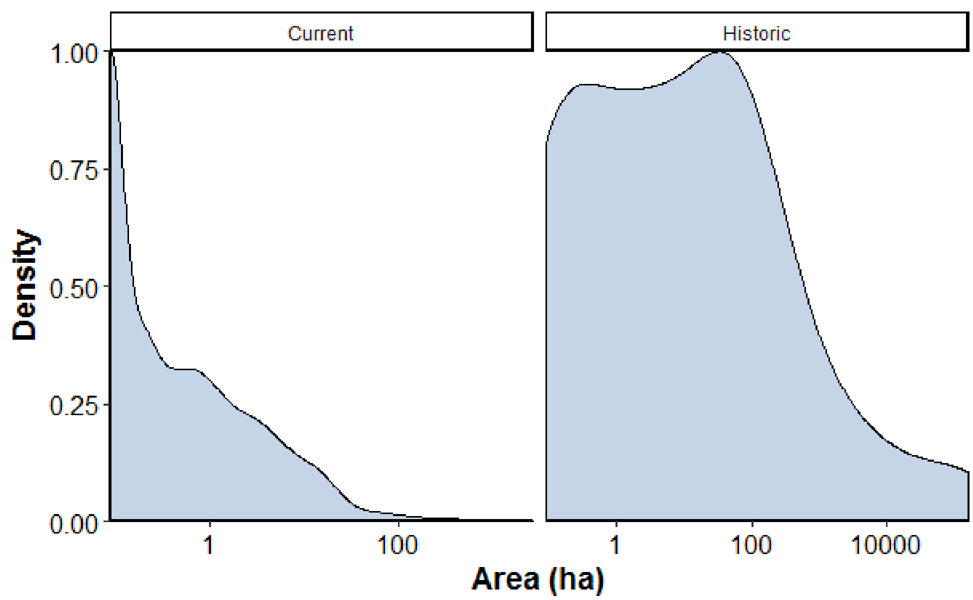

Figure 3. Change in wetland area distribution. Probability density functions (pdf) of the historic and modern Delta. Both pdfs are right-skewed, but historically wetland patches had the highest probability of being 100 ha and currently a wetland patch less than 1 ha has the highest probability of occurrence.

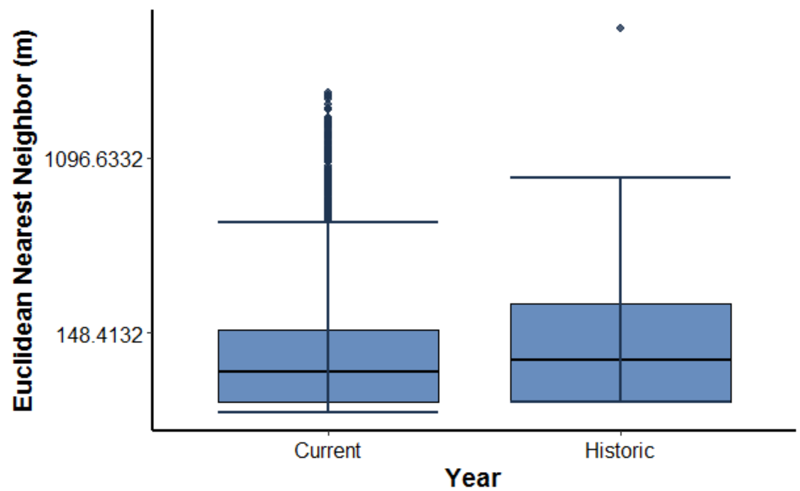

Figure 4. Change in wetland Euclidean nearest neighbor. Boxplots showing the difference in distances between wetlands for the current and historic Delta. The current Delta has many outliers with large Euclidean nearest neighbor distances which may be artificially increasing the mean for the current Delta. This indicates that there is a high amount of variability for distances between wetlands patches.

Table 2. Landscape metrics for historic and current wetlands.

Wetland Year	Mean Patch Size (ha)	Mean Patch Size Standard Deviation (ha)	Percentage of Landscape (%)	Number of Patches	Mean PARA	Mean Euclidean Nearest Neighbor (m)
Current	4.94	54	8.4	2920	914.07	168.8866
Historic	4425.46	22834	76.7	55	502.31	259.0274

Spatial analysis of shrinkage and fragmentation

There was a shift in the spatial distribution of wetlands from the 1800s to the present. Spatial analysis of the average nearest neighbor for the historic wetland distribution show a pattern of statistically significant clustering (p-value<0.01, z-score = -14.538). The spatial distribution of modern wetlands show a pattern of statistically significant dispersion (p-value = 0.000047 and z-score = 4.067). A map displaying the changes in wetland distributions is shown in Figure 5.

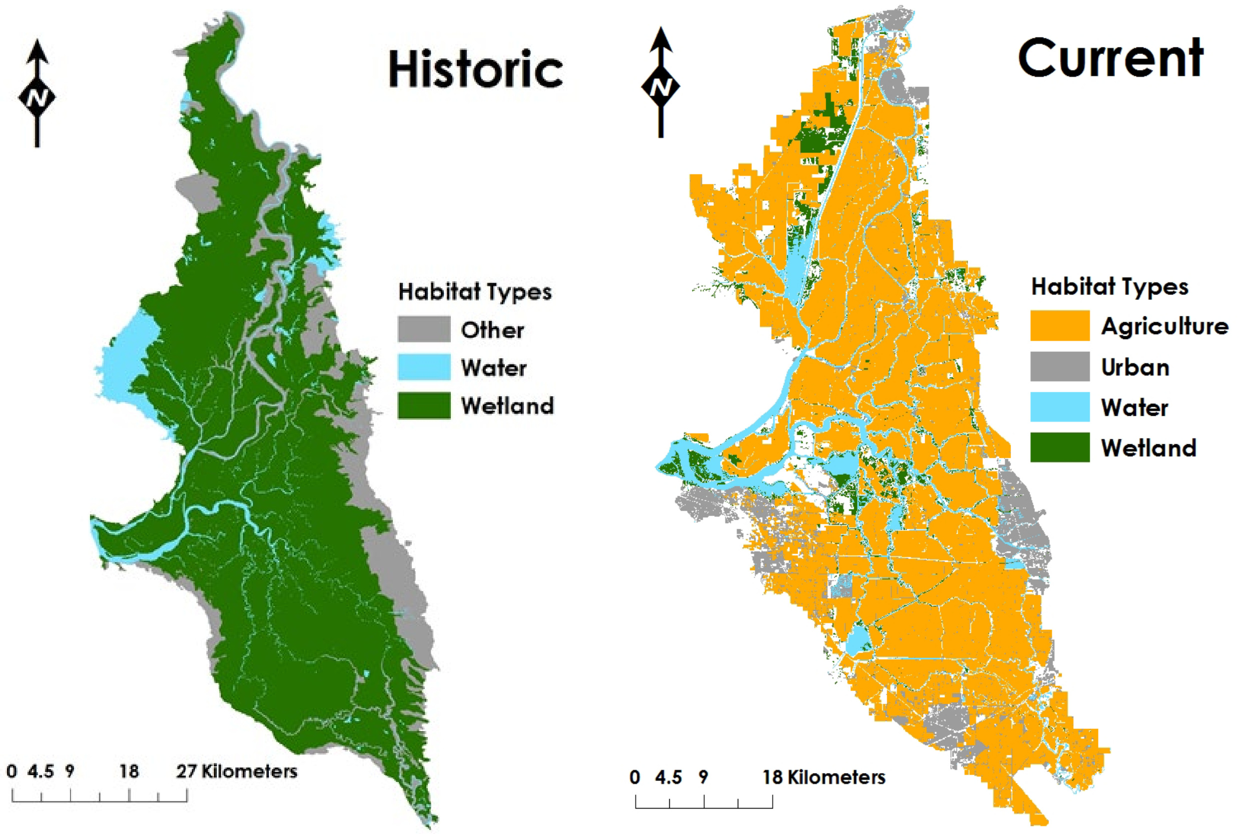

Figure 5. Maps showing the change in dominant land cover types from the historic to modern Delta. Wetland land cover type is indicated in green and agriculture land cover is indicated in orange.

DISCUSSION

Consistent with previous studies, my results show that there have been significant changes in the Delta landscape since 1800s. The percentage of wetland habitat in the Delta has significantly decreased and the spatial distributions of wetlands have shifted from being clustered to being dispersed. In addition, the number of wetlands patches has increased and individual freshwater emergent wetland patches have decreased in area and shape complexity. Human disturbances such as increased urbanization and agriculture in the Delta have made the modern landscape unrecognizable from the 1800s. This makes it more important than ever to understand how the landscape has changed in order to better inform restorations.

Shrinkage and fragmentation

Landscape metrics

The most noticeable change in the Delta is the shrinkage and fragmentation of wetland area. The historic Delta had a mean wetland patch size of 4,425 ha, while the modern Delta has a mean wetland patch size of 5 ha. The number of wetland patches in the historic Delta was 54 and the modern Delta has over 2,000 wetland patches. Robinson et al. 2014 found that there were historically 43 wetland patches in the Delta with a mean patch size of 4,494 ha and that there are currently 1,211 wetland patches with a mean patch size of 4 ha. While our findings are on the same order of magnitude, the differences could be attributed to the use of different datasets to represent the modern Delta. For my analysis I used the U.S. Fish and Wildlife's National Wetland Inventory 2009 dataset, while Robinson et al. 2014 used the Vegetation Classification and Mapping Program's (VegCAMP) 2007 Sacramento-San Joaquin River Delta dataset ('CDFG 2007 Delta Vegetation') as their primary dataset. The different years in which the datasets were created could impact the amount of habitat area that is classified as wetland thereby leading to the observed variations in our results.

The extensive wetland habitat loss that has occurred in the Delta has been documented in other historically wetland dominated landscapes, such as in Northeastern China and the Prairie Pothole Region of Iowa (Wang et al. 2011, Van Meter and Basu 2015). One of the primary factors causing habitat loss in Northeastern China was the transformation of wetlands into agricultural land (Wang et al. 2011). This is also a driving factor in wetland habitat loss in the Delta as over 70% of the Delta is used for agriculture. Wetlands are commonly drained and used for agriculture because their organic matter-rich soils are highly productive, but the process of wetland drainage destroys overall landscape functionality (Zedler 2003, Blann et al. 2009, Johnson et al. 2010, Maltby and Acreman 2011, Deverel and Leighton 2010).

In addition to significant area loss from land conversion, many wetland patches in the current Delta have an increased amount edge habitat. The combination of increased perimeter-area ratio of wetland patches (indicating increased shape irregulatity and edge habitat), high amounts of agricultural land surrounding wetland patches, and decreased wetland patch area makes wetlands in the Delta particularly vulnerable to invasive and other non-native species changing community and food-web structures (Robinson et al. 2014). A common feature of habitat shrinkage and fragmentation is an increase in habitat edge or tranisiont zones that allow for increased occurences of non-native species (Laurance and Yensen 1991). Edge effects or changes in popluation structure that occur at the boundary of two habitats, are especially powerful forces when habitat fragments are small or irregularly shaped, or when the gradient between natural habitats and human-dominated land cover is steep (Laurance and Yensen 1991, Angelstam 1986).

The overwhelming loss of wetlands in the Delta has also led to loss of wildlife support. There are few wetland patches that are large enough to support self-sustaining populations, making wildlife in the Delta particularly vulnerable to catastrophic events (Robinson et al. 2014). Though managed wetlands in the modern Delta provide habitat for wintering and nesting waterfowl they are usually too small and not hydrologically connected to other wetlands, preventing other native wildlife communities from being supported (Robinson et al. 2014). Since smaller, fragmented wetland patches are unable to support large, diverse populations this can lead to reduced population viability, decreased chance of recolonization events, increased risk of extirpation, and reduced genetic diversity (Beedy 1989, Robinson et al. 2014). High genetic diversity is extremely important for populations to be able to adapt to a changing environment (Robinson et al. 2014). With climate change inducing higher levels of droughts in certain regions, having larger more connected habitats is essential for species populations to be resilient to current and future climatic variability (Oliver et al. 2013).

Spatial analysis

Wetlands in the modern Delta are significantly more spatially dispersed than wetlands in the historic Delta. Historically, wetland patches were close together and only separated by rivers or riparian forests which allowed for wildlife movement between wetland patches (Robinson et al. 2014). Currently, wetlands are clusters of much smaller patches that are isolated from other clusters of wetlands. These wetland patches are separated by stretches of human dominated landscapes such as urban areas or agricultural land, significantly impacting wildlife movement (Robinson et al. 2014). Heavy fragmentation of wetlands and increased distances between clusters of fragmented habitat has many potential ecologically damaging effects, such as increased difficulty of species dispersal, increased edge effects (e.g. higher presence of invasive species and less core habitat), and higher chances of small, isolated populations that are less likely to recover from catastrophic events (Robinson et al. 2014, Howe and Simenstad 2011). The high degree of spatial dispersion could potentially be due to restoration site choices being constrained to specific areas of the Delta due to the increases in agriculture and urbanization.

Conservation management could be greatly improved if resources were properly spatially allocated (Arponen et al. 2013). This acts as support for the importance of understanding the spatial makeup of a landscape in order to improve which sites are chosen for restoration. Since the Delta has undergone a significant transformation since the 1800s, it is unlikely that the landscape will ever be restored to its pre-human disturbed state. However, through having a more thorough understanding of how the landscape used to look and what anthropogenic changes have occurred in the Delta, more informed restoration decisions can be made.

Approaching restoration in an agriculturally-dominated landscape

Given all the changes the Delta has undergone, it is important to have current and future restorations aimed at increasing structural functionality of the Delta at a landscape level. Restoration should focus on increasing connectivity of wetland habitats in order to enhance gene flow and movements of organisms between wetland patches (Hood 2007). The configuration of wetland patches should support native wildlife by incorporating landscape-level processes necessary for species viability, such as re-establishing the link between marshes and floodplains (Beedy 1989). Prioritizing this connection between wetlands and open water will help to maintain physical processes integral to ecosystem-wide functionality, such as increased nutrient exchange (Beedy 1989). In addition to restoration efforts aimed at increasing connectivity of historical habitats, expanding upon wildlife friendly agriculture could aid in increasing habitats available for animal species in an agriculture-dominated landscape. Examples of this are flooded rice fields at Knaggs Ranch in the Yolo Bypass that provide rearing habitat for salmon and summer flooded fallow fields in the Yolo Bypass area that provide habitat for migrating shorebirds (Robinson et al. 2016).

Limitations and future directions

This study primarily focused on gaining an understanding of how general properties of wetland size, shape, and distribution have changed over time. Robinson et al. 2014 found that the average distance to large wetland patch historically was 0.29 km, but the average distance currently is 19.3 km. I found that the average distance between wetland patches of any size was historically 0.23 km and is currently 0.45 km. I used the raw data from the NWI dataset without any pre-processing in order to calculate average distance between patches. Robinson et al. 2014 calculated the distance of each wetland patch to nearest neighboring wetland patch that was greater than 100 ha. The reason they choose a wetland patch of 100 ha was because research has indicated that there is a negative correlation between California Black Rail presence and distance to nearest 100 ha wetland patch (Moyle et al. 2012). The difference in the ways that we calculated distances between wetland patches highlights the need for a standardized method or guideline for determining distances between wetland patches. Future studies looking into what datasets are most appropriate to use for calculation of landscape metrics and spatial distribution of wetland habitats is crucial to improving consistency in restoration monitoring techniques.

Broader implications

This study highlights key changes that have occurred in the Delta since the 1800s. A better understanding of these changes will help to inform which restoration activities should be of primary focus in order to increase restoration performance. Deverel and Leighton 2010 found that Delta land surface elevations will decrease by over 1.3 m by 2050 and that the largest elevation loss will occur in the central delta. Focusing on areas that are less likely to be affected by subsidence and sea level rise will ensure that the restoration efforts have lasting effects. Changing land-management practices so that soil organic matter content is decreased, less burning occurs, and less wind erosion occurs will help to reduce subsidence over time (Deverel and Leighton 2010). Proper placement of restoration sites and reduction of subsidence-inducing land management practices will help to improve the overall landscape of the Delta. Based off of my study and others findings, I suggest restoration efforts be focused in areas at higher elevations, places where high amount of sediment buildup occur, and areas that are close to other wetlands.

There is a need for restoration projects to integrate ecosystem wide functionality and this paper outlined what broad efforts could help to address this need. Drawing on past and present changes in the Delta will help to improve our overall understanding of the landscape and which restoration techniques are most useful in degraded wetland ecosystems.

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