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Alameda Song Sparrow Abundance Related to Salt Marsh Vegetation Patch Size and Shape Metrics Quantified from Remote Sensing Imagery

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Abstract:

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Understanding the characteristics of high-quality avian habitat is critical for guiding salt marsh management and restoration. Existing insights into salt marsh avian habitat are often based on the composition of marsh vegetation, e.g., individual plant species cover. This study investigated whether the spatial configuration of marsh surface cover (e.g., patch number, density, size, shape complexity and compactness, degree of dissection of the landscape, variation and repetition of cover type, and the variance within these metrics) is a useful, additional indicator of avian habitat quality for the Alameda Song Sparrow (*Melospiza melodia pusillula*), a non-migratory California Species of Special Concern endemic to southern San Francisco Bay. *M. m. pusillula* density during the breeding seasons of 2002 through 2005 was estimated at 82 observation points in 10 marsh sites within the bird's geographic range. The mean bird density index (overall mean: 5.61 birds detected per hectare of marsh) was not significantly different among marshes of different ages. We mapped the vegetation zones, open water, and upland areas within each marsh site using high resolution aerial photographs and automated classification analysis. We quantified the configuration of surface cover around each bird observation point by 31 metrics. Bird density index was best modeled by a multiple linear regression containing positive relationships with the metrics Mean Core Area Index and Patch Core Area Coefficient of Variation ($R^2 = 0.210$, $p < 0.0001$). Qualitatively, this model suggested that *M. m. pusillula* abundance during the breeding season was greatest in marsh areas with compact patches that spanned a variety of patch sizes from moderate-to-large, uninterrupted by other cover. We conclude that configuration-based vegetation pattern analysis could usefully complement more customary composition-based habitat assessments to aid wetland habitat research, management, and restoration.

Supporting material:

Appendix A: True Color Ortho-Photography and Classified Marsh Cover Maps for Ten Marsh Study Sites
Appendix B: Definitions of Quantitative Metrics of Vegetation Configuration

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Alameda Song Sparrow Abundance Related to Salt Marsh Vegetation Patch Size and Shape Metrics Quantified from Remote Sensing Imagery

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ABSTRACT

Understanding the characteristics of high-quality avian habitat is critical for guiding salt marsh management and restoration. Existing insights into salt marsh avian habitat are often based on the composition of marsh vegetation, e.g., individual plant species cover. This study investigated whether the spatial configuration of marsh surface cover (e.g., patch number, density, size, shape complexity and compactness, degree of dissection of the landscape, variation and repetition of cover type, and the variance within these metrics) is a useful, additional indicator of avian habitat quality for the Alameda Song Sparrow (*Melospiza melodia pusillula*), a non-migratory California Species of Special Concern endemic to southern San Francisco Bay. *M. m. pusillula* density during the breeding seasons of 2002 through 2005 was estimated at 82 observation points in 10 marsh sites within the bird's geographic range. The mean bird density index (overall mean: 5.61 birds detected per hectare of marsh) was not significantly different among marshes of different ages. We mapped the vegetation zones, open water, and upland areas within each marsh site using high resolution aerial photographs and automated classification analysis. We quantified the configuration of surface cover around each bird observation point by 31 metrics. Bird density index was best modeled by a multiple linear regression containing positive relationships with the metrics Mean Core Area Index and Patch Core Area Coefficient of Variation ($R^2 = 0.210$, $p < 0.0001$). Qualitatively, this model suggested that *M. m. pusillula* abundance during the breeding season was greatest in marsh areas with compact patches that spanned a variety of patch sizes from moderate-to-large, uninterrupted by other cover. We conclude that configuration-based vegetation pattern analysis could usefully complement more customary composition-based habitat assessments to aid wetland habitat research, management, and restoration.

KEY WORDS

population density, song sparrow, spatial pattern analysis, vegetation configuration, wetland restoration, salt marsh, tidal marsh

INTRODUCTION

The native flora and fauna of San Francisco Estuary (estuary) tidal salt marshes have been affected by 160 years of conversion to salt ponds, urban development, and fill (Atwater et al. 1979; Wells 1995; Sloan 2006). Habitat loss is particularly detrimental to non-migratory, endemic species such as the Alameda song sparrow, *Melospiza melodia pusillula*. With only 10% of its historical habitat remaining, *M. m. pusillula* is the most threatened by salt marsh habitat loss among the three regionally endemic subspecies of song sparrow (Nur et al. 1997); it is also the most genetically distinct (Cogswell 2000; Chan and Arcese 2002). Currently, the South Bay Salt Pond Restoration Project is progressing toward restoring about 60 km^2 (15,100 acres) to salt marshes and managed tidal ponds within the *M. m. pusillula* range. Preserving biodiversity by restoring threatened flora and fauna habitat is among the key goals of this significant undertaking (SBSPRP 2004). However, the specific salt marsh characteristics that provide good *M. m. pusillula* habitat are incompletely understood.

M. m. pusillula is a California State Bird Species of Special Concern on the basis of its endemism, small range size, diminished population, population concentration among relatively few sites, and risk of continued future habitat degradation (Chan and Spautz 2008). The range of *M. m. pusillula* is limited to the southern and eastern shores of the estuary (Marshall 1948; Marshall and Dedrick 1993; Chan and Spautz 2008). Historical population estimates ranged from 73,050 birds (Marshall and Dedrick 1993) to 138,000 birds (Chan and Spautz 2008) before 19th-century land development around the estuary. Recent estimates suggest a current population of 12,000 to 18,000 birds (Nur and Spautz 2002). Identifying and managing for tidal marsh characteristics that are associated with high bird abundance is one way to increase population size. Both the spatial composition and the spatial configuration of habitat influence the abundance and distribution of fauna (McGarigal and McComb 1995; Wiens 1995; Turner et al. 2001).

In salt marshes, studies have so far focused mainly on the composition of habitat: e.g., the types and relative abundance of marsh cover classes (water, channel, mudflat, vegetation); individual plant species' cover or diversity, or vegetation height, density, greenness, or productivity. Studies have also tested relationships between salt marsh bird habitat and non-vegetation characteristics such as marsh size; age; elevation; salinity; channelization; rainfall; tidal regime; water depth; isolation; and the types of, proportions of, and distances to adjacent land uses (Leonard and Picman 1987; Lauro and Burger 1989; Craig and Beal 1992; Zedler 1993; Weller 1994; Nur et al. 1997; Benoit and Askins 1999, 2002; Isacch et al. 2004; Gjerdrum et al. 2005, 2008; Spautz et al. 2006; Takekawa et al. 2006; Wilson et al. 2007; Tian et al. 2008; Kelly et al. 2008; Tsao et al. 2009; Bayard and Elphick, 2010; Stralberg et al. 2010; Ma et al. 2011).

Relationships of bird habitat to the configuration of surface cover in salt marshes have been much less studied than relationships with surface composition (Lauro and Burger, 1989; Pearson et al. 1992; Nur et al. 1997; Spautz et al. 2006; Bayard and Elphick 2010). Metrics can characterize surface configuration by quantifying vegetation zone, water, or upland patches' number, density, size, shape complexity and compactness, degree of dissection of the landscape, variation and repetition of patch type, and the variance within these metrics.

Configuration-based assessment of bird habitat in salt marshes is likely to be informative since aspects of vegetation configuration have been correlated with habitat use by birds in other environments (Saab 1999; Graham and Blake 2001; Crozier and Niemi 2003; Westphal et al. 2003; Cushman and McGarigal 2004; Cornulier and Bretagnolle 2006; Koper and Schmiegelow 2006; Rehm and Baldassarre 2007; Sripanomyom et al. 2011). Most of these studies focused on the landscape configuration within which the specific bird habitat of interest was located (e.g., adjacency of upland, development, or agriculture; proximity of other similar habitat). For example, Saab (1999) found that, for the occurrence of most of 32 bird species among riparian cottonwood trees in Idaho, the adjacency of upland or agriculture was more important than characteristics of the tree clusters themselves. In contrast, Crozier and Niemi (2003) found that broader landscape characteristics were not as useful as characteristics of individual land cover types, mainly area, for explaining bird abundances in a heterogeneous landscape of natural forests and wetlands in upper Michigan. However, Graham and Blake (2001) found that bird species restricted to forest stands were not influenced by landscape characteristics beyond the stands but non-restricted species were influenced by both stand and landscape characteristics in a pasture-dominated area of Veracruz, Mexico. Extrapolating from the findings of Graham and Blake (2001) suggests the hypothesis that for *M. m. pusillula*, which is restricted to salt marshes, abundance would not be strongly influenced by landscape characteristics outside the home marsh, which is also suggested by Stralberg et al. (2010). However, this leaves open the question of what influence the configuration of patches (on the order of meters to tens of meters wide) of marsh surface cover within the home marsh may have on bird abundance. For example, some southern estuary marshes are qualitatively composed mostly of one large patch of a dominant vegetation type interrupted by only very small stands of another type, while other marshes are composed of many small patches of different cover types juxtaposed like a mosaic. The literature provides little indication of how this cover configuration within a given marsh might relate to *M. m. pusillula* abundance.

The types of cover (composition) in which *M. m. pusillula* is found are understood in more detail than are the patterns of cover (configuration) in which the birds tend to live. *M. m. pusillula* is found only in marshes that are tidally influenced (Marshall 1948; Cogswell 2000). The subspecies is found throughout a tidal salt marsh among almost any type of vegetation (H. T. Harvey & Associates, 2005), though it sometimes concentrates in taller creek-bank vegetation (Marshall 1948). Birds take refuge from high tides on floating debris, tall *Grindelia* spp. bushes, and man-made levees (Johnston 1955; Cogswell 2000). In the San Francisco Estuary region, the species (*Melospiza melodia* subsp.) nests in all the major salt marsh plant species (*Sarcocornia* spp., *Grindelia* spp., *Spartina* spp.) but avoids the tallest bushes, which are likely prone to higher predation, and the shortest stems, which are prone to flooding (Marshall 1948; Johnston 1956a, 1956b). Birds nest in both native and invasive *Spartina* spp. but have greater nest success in native *Spartina foliosa* (Nordby et al. 2009). Within a marsh, song sparrow abundance has been positively correlated with tall shrub cover (*Grindelia stricta* and *Bachharis pilularis*), negatively correlated with pond, pan, and sparse rush (*Juncus* spp.) cover (Spautz et al. 2006), positively correlated with the degree of channelization (Nur et al. 1997), and positively correlated with salinity, channel proximity and area, and cover of tall bulrush (*Schoenoplectus acutus/californicus*) and some other species (Stralberg et al. 2010). Site specific, within-marsh factors are thought to dominate song sparrow population prediction (Stralberg et al. 2010). Despite these known aspects of *M. m. pusillula* habitat association, it remains incompletely understood why one area of a marsh may be occupied densely by *M. m. pusillula* while another area with similar composition is occupied only sparsely. It is also not well understood how marsh age or restoration status (natural vs. restored) affects *M. m. pusillula* density (Wood et al. 2009).

We hypothesized that spatial variation in *M. m. pusillula* density is partly related to variations in the configuration of surface cover within a marsh. Although three studies have investigated the relationships of *M. melodia* subsp. abundance to salt marsh configuration as well as to composition (Nur et al. 1997; Spautz et al. 2006; Stralberg et al. 2010), they assessed the combined habitat of multiple song sparrow subspecies and tested only a few metrics that quantify surface cover configuration (mainly configuration of marsh within the greater landscape, not cover within a marsh), resulting in regression models explaining 17% to 38% of the variance in song sparrow abundance. Since the *M. m. pusillula* subspecies is the most distinct in the region (Cogswell 2000; Chan and Arcese 2002) and since its abundance varies over four orders of magnitude among the marshes in its range (Nur et al. 1997) a study of this subspecies, individually, is warranted. In this study, we compiled unpublished data on *M. m. pusillula* population density index from 2002 through 2005 and explored whether aspects of spatial marsh cover configuration not previously examined might also explain some of the wide variance in *M. m. pusillula* abundance.

METHODS

Study Area

We analyzed 10 salt marshes that fringe the southern estuary, occupying a total of 669 ha (Figure 1). These sites covered 25% to 50% of the total *M. m. pusillula* habitat range, depending on the total range estimate used (Marshall 1948; Nur et al. 1997) and constituted all of the marshes within the range for which population density index data were available for the years 2002 through 2005. We chose this study period as that most closely relevant to the time at which high-resolution aerial imagery of the marshes was collected (late 2003 to early 2004). We obtained marsh ages and restoration dates from the literature (SFEI 1997; Wetlands and Water Resources, Inc. 2003).

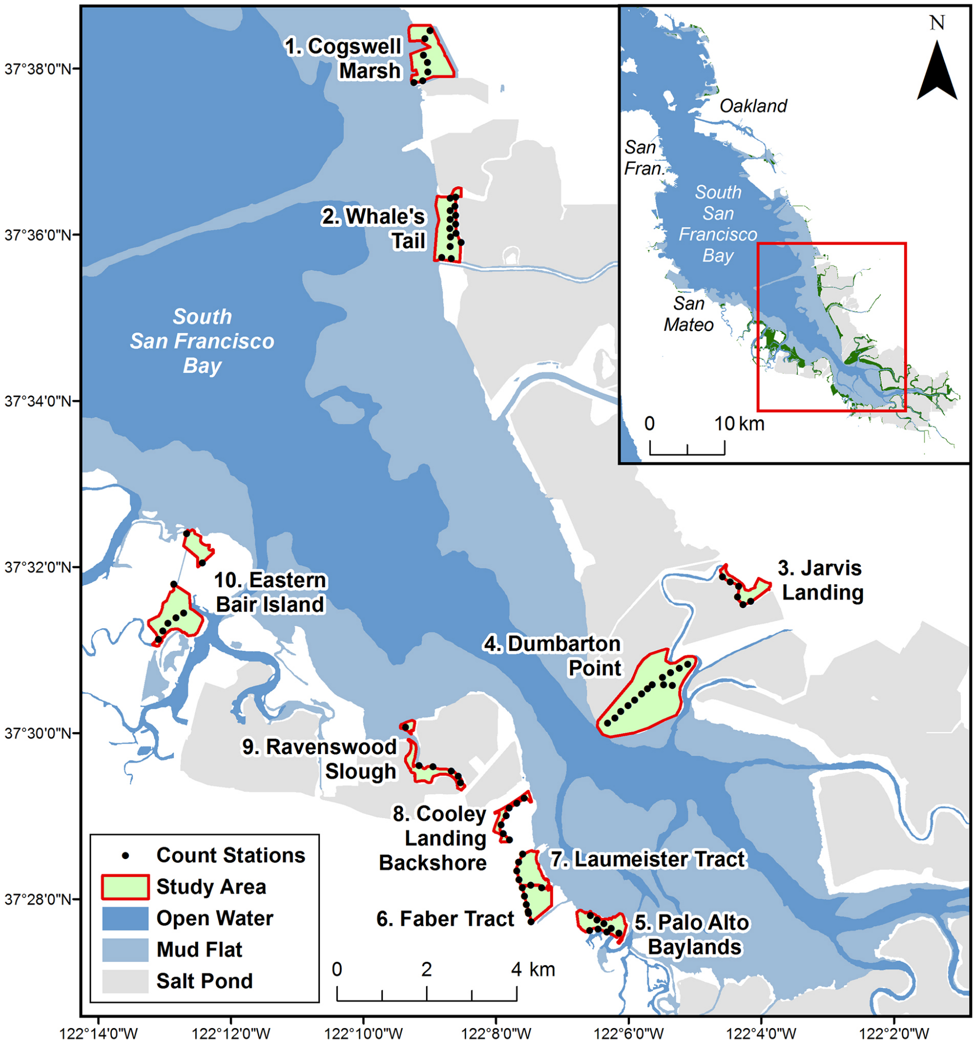


Figure 1 Locations of ten marsh sites within southern San Francisco Bay study area. Inset: study area location (red box) and tidal marshes that are *M. m. pusillula* habitat (in dark green).

M. m. pusillula Point Counts

M. m. pusillula population surveys were conducted during the breeding seasons of 2002 to 2005 between March 20 and May 31. March to May is the most appropriate time to survey birds that may be breeding or attempting to breed and matches the timing used by related studies (Nur et al. 1997; Spautz et al. 2006; Stralberg et al. 2010). Point count stations were located every 150 to 200 m along marsh access ways, typically levees bordering the marsh but occasionally levees or boardwalks cross-cutting the marsh. At each station, trained and experienced surveyors counted every bird identifiable by sight or sound within 5 min and estimated the distance from the station to the bird according to the Variable Circular Plot method (Reynolds et al. 1980; Nur et al. 1997; Spautz et al. 2006). An index of bird density (birds detected per hectare marsh) was calculated as the total number of detections within a 50-m radius of the station, relative to the fraction of tidal marsh habitat present within the 50-m observation area (Nur et al. 1997; Spautz et al. 2006). The density index values for each point count station were averaged over the years 2002 through 2005. This period was chosen to span one year before and after the time of the aerial photography, to ensure sufficient data for analysis. Accordingly, our analysis was based on average population density index values for 82 stations distributed across 10 marshes. The bird density index gives an estimate of relative abundance, which provides a reliable proxy of true density (e.g., compared to estimates of absolute density using the program DISTANCE; specifically, Nur et al. [1997], which found that detection probability did not vary significantly among tidal marshes using these methods).

Marsh Cover Analysis

We analyzed the configuration of marsh surface cover types within the 50-m-radius observation area that surrounds each point count station in two steps. First, we mapped the major cover classes (major vegetation zones, water, upland/other) throughout each marsh site based on remote sensing imagery and ground observations (see also "Marsh Cover Mapping"). Second, we extracted the observation area around each point count station from the marsh-wide cover map and quantified the configuration of cover within each extracted observation area by 31 different metrics (see also "Marsh Cover Configuration Quantification").

Marsh Cover Mapping

We mapped each marsh site independently since the spectral signatures of different covers in the aerial photography varied somewhat between images. The imagery used was high-resolution (0.3-m pixel size), georeferenced, visual spectrum (three-band RGB), aerial ortho-photographs acquired between October 20, 2003 and January 21, 2004 (EarthData International 2004). We defined training areas by visually inspecting the imagery, informed by field observations. Our selection of training areas was facilitated by the presence of only a few dominant plant species (Atwater et al. 1979). Maximum-likelihood supervised classifications (MLSC) (Richards 2012) in ENVI 4.6.1 (ITT, Boulder, CO) divided each study site into six cover classes:

1. water (bay, ponds, and tidal channels);
2. non-tidal uplands and objects (levees, wrack, man-made structures, and dark shadows);
3. predominantly *Sarcocornia pacifica* (a.k.a. *Salicornia virginica*);
4. predominantly *Spartina foliosa* (possible admixture of invasive *Spartina alterniflora* and hybrids);
5. bright green vegetation, usually *Frankenia salina*, *Jaumea carnosa*, and/or *Distichlis spicata*; and
6. predominantly *Grindelia stricta* or *Bolboschoenus maritimus* (a.k.a. *Scirpus maritimus*).

Further separating the fifth class into *Frankenia salina*, *Jaumea carnosa*, or *Distichlis spicata* was deemed unnecessary because these are all low-lying herbaceous species unlikely to be used by *M. m. pusillula* for nesting because they flood frequently (Marshall 1948; Johnston 1956a, 1956b). Further separating the sixth class into *Grindelia stricta* or *Bolboschoenus* *maritimus* was not possible using MLSC, which produced “speckled” patches incorrectly classified as a complex mix of the two species. Since the two species actually grow in different portions of the marsh, in reality they are rarely found adjacent or within the same 50-m-radius observation area patch. To mitigate the MLSC error and “speckling,” we combined the two classes. Therefore, within a given observation area, the sixth class represented either *Grindelia stricta* or *Bolboschoenus maritimus* depending on the area’s position in the marsh. These combined classes were therefore adequate to assess only the spatial marsh cover configurations the birds occupied.

The statistical separability of the six cover classes resulting from MLSC was high (ENVI 4.6.1, ITT, Boulder, CO), indicating that the winter-season imagery was adequate to distinguish and map the spatial patterns of these broad classes. We further improved the classifications manually: a combination of MLSC and manual delineation of some features is commonly used to classify wetland vegetation from remotely-sensed imagery (Tuxen and Kelly 2008; Stralberg et al. 2010). This combined approach is required in cases where large features visually identifiable in the imagery (e.g., water, levees) are poorly mapped by automated MLSC. For example, water appeared in the marsh imagery in many different colors that MLSC often incorrectly classified as various vegetation assemblages. In these cases, we used ArcGIS 9.3.1 (ESRI, Redlands, CA) to manually delineate the features using vector outlines and to reassign them, via vector-based raster selection, to the correct cover class. The classified cover maps for each marsh site are illustrated in Figure 2. Note that the classified maps were not intended to precisely identify vegetation species, only to capture the spatial patterns of cover.

Marsh Cover Configuration Quantification

To analyze the patterns of marsh cover surrounding each point count station, we clipped the classified cover maps using a 50-m buffer around each point (using ArcGIS 9.3.1). The 50-m radius corresponded with the radius of detection used in the Variable Circular Plot method. In cases where the marsh edge or imagery boundary truncated a 50-m circle, we clipped the circle so it would not contain empty pixels. We termed the resulting circular or sub-circular marsh landscapes “observation areas.” A spatial analysis program (Patch Analyst 4 [Rempel and Carr 2003] based on FRAGSTATS by McGarigal and Marks 1995) was used to calculate 31 metrics that describe the configuration of patches of different marsh covers within each observation area. This approach was similar to that used by of other studies of bird abundance in relation to landscape characteristics within observation areas of finite radius (Mita et al. 2007; Kelly et al. 2008; LeDee et al. 2008; Stralberg et al. 2010; Sripanomyom et al. 2011). It is worth emphasizing that we quantified the configuration metrics used in this study only within the 50-m radius observation areas, and separately for each observation area. In the parlance of the analysis software (Patch Analyst, FRAGSTATS, etc.), we treated each observation area as its own “landscape” and quantified the shapes and configuration of the “patches” of each marsh cover “class” within the observation area. This approach differed from that of other related studies that treated the entire marsh (or tree grove, etc.) as a “patch” and evaluated the spatial qualities and relationships of marshes to each other within a larger regional landscape (e.g., Saab 1999; Graham and Blake 2001; Crozier and Niemi 2003; Spautz et al. 2006).

The 31 quantitative cover configuration metrics, listed in Table 1 and described in Appendix B, covered a few general categories: observation area size and shape, patch regularity and compactness, diversity of patches and cover classes, pattern configuration and evenness, and patch core area metrics. A core area is the area of a patch located more than a specified distance from the edge (1 pixel = 0.3 m, in this study). Our choice of edge distance balanced a trade-off: capturing sub-pixel uncertainty in patch border location in the “edge” and preventing very small patches from representing core area, but minimally infringing on the core area of the moderately small patches characteristic of these marshes. The mean patch area in the study was 2.81 (± 1.34 m^2 standard deviation), or equivalent patch radius of 0.95 ± 0.65 m.

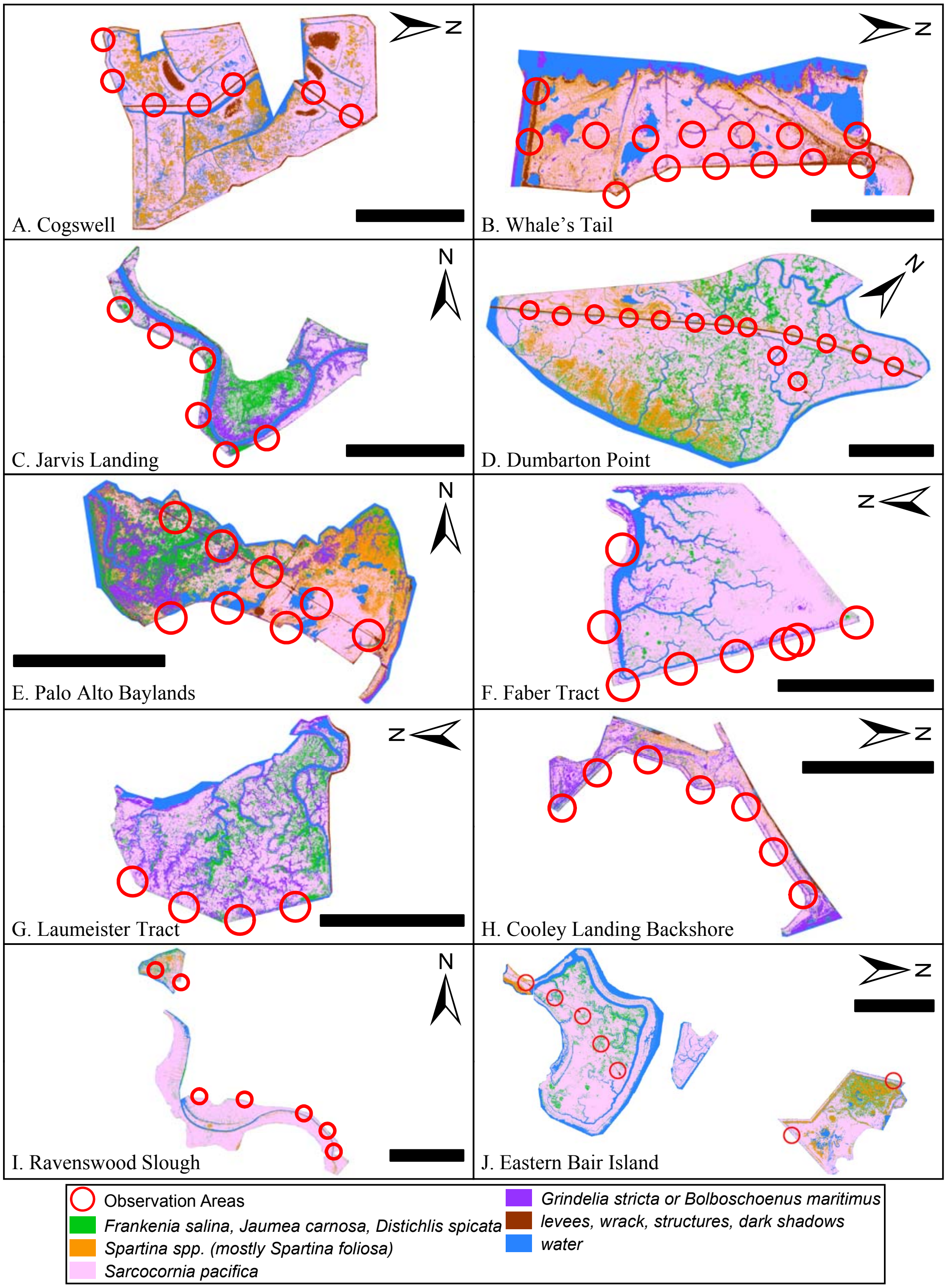


Figure 2 Classified marsh cover maps. Scale bars are 500-m long. Background imagery and larger versions of classified maps are provided in Appendix A.

Table 1 Univariate correlations (*r*) and significance (*p*) between *M. m. pusillula* density index (birds detected ha^{-1}) and metrics describing the configuration of marsh surface cover within 50 m of the bird point count stations. Mean and standard deviation of metric values among all 82 observation areas are listed for reference.

Vegetation Pattern Metric		*r*	*p*	μ ± σ
Observation Area Size and Shape				
TLA	Total Landscape Area	0.098	NS[a]	0.571 ± 0.207
TE	Total Edge	0.188	< 0.10[b]	7356 ± 3567
ED	Edge Density	0.037	NS	13294 ± 4874
LSI	Landscape Shape Index	0.140	NS	24.3 ± 9.4
LPI	Largest Patch Index	-0.079	NS	41.8 ± 17.8
Patch Regularity and Compactness				
PSSD	Patch Size Standard Deviation	-0.108	NS	0.00695 ± 0.00489
PSCOV	Patch Size Coefficient of Variance	-0.006	NS	2240 ± 740
MSI	Mean Shape Index	0.245	< 0.05[c]	1.24 ± 0.04
AWMSI	Area-Weighted Mean Shape Index	0.001	NS	11.3 ± 4.8
MPFD	Mean Patch Fractal Dimension	-0.158	< 0.20	0.266 ± 0.255
AWMPFD	Area-Weighted Mean Patch Fractal Dimension	-0.009	NS	1.39 ± 0.12
Diversity of Patches and Classes				
NUMP	Number of Patches	0.135	NS	2353 ± 1278
PR	Patch Richness	0.025	NS	4.78 ± 0.79
PRD	Patch Richness Density	-0.112	NS	959 ± 401
SDI	Shannon's Diversity Index	0.176	< 0.20	1.01 ± 0.29
MSIDI	Modified Simpson's Diversity Index	0.173	< 0.20	0.794 ± 0.790
Pattern Evenness and Configuration				
MNN	Mean Nearest Neighbor	-0.164	< 0.20	0.593 ± 0.107
MPI	Mean Proximity Index	0.124	NS	1056 ± 545
IJI	Interspersion Juxtaposition Index	-0.044	NS	59.0 ± 12.7
SHEI	Shannon's Evenness Index	0.156	< 0.20	0.522 ± 0.154
SEI	Simpson's Evenness Index	0.179	< 0.20	0.651 ± 0.159
MSIEI	Modified Simpson's Evenness Index	0.173	< 0.20	0.506 ± 0.198
Patch Core Area Metrics				
NCA	Number of Core Areas	0.203	< 0.10[b]	652 ± 397
TCA	Total Core Area (ha)	-0.008	NS	0.342 ± 0.166
CAD	Core Area Density	0.083	NS	118240 ± 60507
MCAI	Mean Core Area Index	0.367	< 0.05[c]	1.18 ± 0.50
TCAI	Total Core Area Index	-0.052	NS	58.4 ± 14.1
CASD1	Patch Core Area Standard Deviation	-0.074	NS	0.00378 ± 0.00488
CASD	Disjunct Core Area Standard Deviation	-0.209	< 0.10[b]	0.00878 ± 0.00780
CACV1	Patch Core Area Coefficient of Variation	0.055	NS	2723 ± 911
CACOV	Disjunct Core Area Coefficient of Variation	-0.040	NS	5399 ± 2163

For df = 80:

a. NS is $p > 0.20$, $|r| \geq 0.143$.

b. $p < 0.10$ is $|r| \geq 0.183$.

c. $p < 0.05$ is $|r| \geq 0.217$.

Increasing the edge distance beyond 0.3 m would have further eroded potential core area to well less than half the average patch area (for a circular patch equivalent). Depending on the patch's shape, there may be zero, one, or multiple disjunct core areas per patch.

Statistical Analysis

We evaluated differences in the mean *M. m. pusillula* density index among old (>160 yrs), "centennial" (<160 yrs, since the Gold Rush), and restored marsh categories using pairwise *t*-tests. We tested relationships between the *M. m. pusillula* density index and the 31 vegetation configuration metrics for each observation area with univariate correlation and multivariable regression analyses. Since bird density is likely to respond simultaneously to multiple characteristics of landscape configuration (Spautz et al. 2006) multiple linear regression analysis was warranted. However, many metrics contain redundant information and may be correlated with one another, thus impeding interpretation (Riitters et al. 1995; Turner et al. 2001). Therefore, we wanted subsets of metrics with low cross-correlations for multivariable regression analysis. We developed four subsets of metrics by examining the cross-correlations among metrics: in an iterative procedure, we removed the metric with the highest absolute value correlation with all the other metrics, on average, from the set until only 25, 20, 15, or 10 metrics remained (Table 2). We then implemented multivariable linear regression models on each of these four subsets. In theory, this *a priori* removal of metrics from the regression analyses is not necessary because a forward stepwise multivariable linear regression approach will select only metrics both correlated with bird density index and relatively independent from previously selected metrics; however, we preferred to still apply this tiered approach to help ensure the final model was robust to differences in the a priori selection of metrics. In each forward stepwise multiple linear regression model conducted using MATLAB software the criterion used to accept a metric for entry to the model was $p \leq 0.05$ (Harrell 2001; Kutner et al. 2004).

Table 2 Four subsets of metrics used in multiple linear regression analyses

Configuration metrics	Included in subset			
	m = 25	m = 20	m = 15	m = 10
TLA	x	x	x	x
TE	x			
ED				
LSI				
LPI	x	x	x	
TLA				
PSSD	x			
PSCOV	x			
MSI	x	x	x	
AWMSI	x	x		
MPFD	x	x	x	x
AWMPFD	x	x	x	x
NUMP	x	x	x	
PR	x	x	x	x
PRD	x	x		
SDI				
MSIDI				
MNN	x	x	x	x
MPI	x	x	x	x
IJI	x	x	x	x
SHEI				
SEI	x	x		
MSIEI	x			
NCA	x	x		
TCA	x	x	x	x
CAD	x	x		
MCAI	x	x	x	x
TCAI				
CASD1	x	x	x	
CASD	x			
CACV1	x	x	x	x
CACOV	x	x	x	

RESULTS

M. m. pusillula Density Index Values

Average bird density index varied from 0.64 to 12.73 birds ha^{-1} (Table 3). The overall median and mean densities were similar: 5.55 and 5.61 birds detected ha^{-1}, respectively.

Relationship of *M. m. pusillula* Density Index to Marsh Age

The means and standard deviations of *M. m. pusillula* density index in marshes of different ages (see Table 3) were: ancient natural marshes, 5.98 ± 2.71 birds detected ha^{-1}; centennial natural marshes, 4.33 ± 2.58 birds birds detected ha^{-1}; restored marshes, 5.32 ± 3.06 birds birds detected ha^{-1}. No significant pairwise differences between the mean bird densities in the different marsh age categories were indicated by *t*-tests at a 95% confidence level. In other words, *M. m. pusillula* density index was statistically similar among marshes thought to predate regional development (more than 160 years old), marshes thought to have developed on sediment deposited since the Gold Rush and since major development of the Sacramento and San Joaquin watersheds (less than 160-year old, referred to as "centennial marshes"), and marshes restored in more recent decades (from 1935 to 1980). This analysis of ten marshes is also supported by analysis of a larger set of marshes (n = 25) that cover the entire geographic range of the Alameda Song Sparrow, which indicated that for 2001 through 2005 the density index was not related to age of marsh (based on linear regression of *ln(density index)* in relation to marsh age, categorized into centennial, middle, and old, $p > 0.9$; J. Wood, Point Blue, unpublished data, see "Notes").

Relationship of *M. m. pusillula* Density Index to Vegetation Configuration

Of the 31 metrics quantifying vegetation configuration in the observation areas, two metrics were significantly correlated with *M. m. pusillula* density index in univariate analyses with $p < 0.05$: Mean Core Area Index (MCAI) and Mean Shape Index (MSI). Three metrics were correlated with density index with $0.05 < p < 0.1$: Disjunct Core Area Standard Deviation (CASD), Number of Core Areas (NCA), and Total Edge (TE). Seven metrics were correlated with density index with $p < 0.2$ (see Table 1).

Table 3 *M. m. pusillula* density index in the observation areas within each marsh in the study area (see Figure 1) from 2002 through 2005

Marsh Site Characteristics				*M. m. pusillula* density index (birds detected ha^{-1})				
Site	**Age**	**Area (ha)**	**n**	**Median**	**Mean**	**Standard Deviation**	**Minimun**	**Maximum**
A. Cogswell Marsh	restored	78	7	1.32	1.92	1.05	0.88	3.43
B. Whale's Tail Marsh	restored	71	14	6.60	7.10	3.13	2.55	12.73
C. Jarvis Landing	old	27	6	6.47	6.52	2.04	3.74	9.20
D. Dumbarton Point	old	224	14	6.40	6.47	1.92	3.50	9.07
E. Palo Alto Baylands	old	39	8	6.53	6.89	2.77	1.75	10.61
F. Faber Tract	restored	36	8	5.43	5.62	1.42	4.09	8.49
G. Laumeister Tract	old	36	4	7.32	7.32	3.31	4.46	10.19
H. Cooley Landing Backshore	old	16	7	1.27	1.73	0.88	0.64	3.18
I. Ravenswood Slough	centennial	38	6	3.66	4.33	2.58	1.91	9.09
J. Eastern Bair Island	old/restored	104	8	6.37	6.25	2.13	2.55	8.91
All marshes		669	82	5.55	5.61	2.85	0.64	12.73

Table 2 denotes which variables were included in each of the four subsets supplied to multiple linear regressions. All four subsets of candidate metrics, when provided to the forward stepwise multiple regression procedure, resulted in the same final model ($R^2 = 0.210$, $p < 0.0001$):

$$\text{Density index} = 3.03\,(\text{MCAI}) + 9.97 \times 10^{-4}\,(\text{CACV1}) - 0.68$$

The two statistically predictive metrics were Mean Core Area Index (MCAI) and Patch Core Area Coefficient of Variation (CACV1).

DISCUSSION

Relationship of *M. m. pusillula* Density Index to Vegetation Patterns

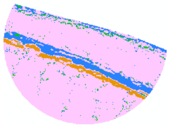
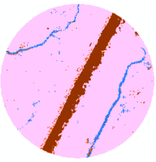
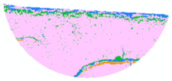
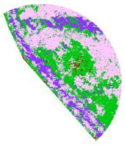
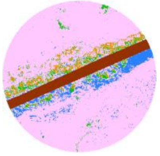
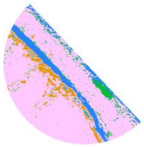
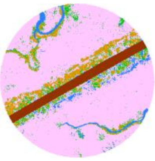
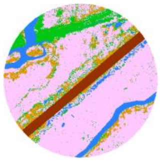
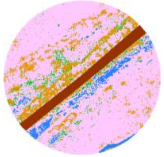
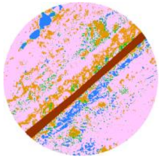
Spatial variation in *M. m. pusillula* breeding season density index was significantly related to MCAI and CACV1. Since MCAI was calculated as a percentage of total observation area, it was the shape and compactness of the patches, not their size, that the metric captured. High CACV1 values were scored by observation areas with a wide range of total core area sizes per patch, which effectively also required an abundance of patches large enough to contain core area; areas dominated by patches of uniform size or very small patches without core area scored low CACV1 values (Figure 3).

Together, the positive relationship of *M. m. pusillula* density index to both MCAI and CACV1 suggested that bird abundance during breeding season was greatest in marsh areas with compact patches of different cover types with core areas that spanned a variety of sizes from moderate to large, uninterrupted by very small patches of other cover types. What is not contained in these results is also interesting: based on our analysis, bird density index was not well explained by the presence of uniform vegetation type, uniform patch size, small (highly spatially fragmented) patches, or long linear or tortuous (non-compact) patch shapes.

Complementing the strong multivariable relationship of bird density index with MCAI and CACV1, qualitative inspection of the univariate correlations between *M. m. pusillula* density index and other metrics was informative. Bird density index was positively correlated with the Mean Shape Index (MSI) and negatively correlated with Mean Patch Fractal Dimension (MPFD), suggesting that density was higher in regions with patches more similar to regular Euclidean shapes (squares). Bird density index was negatively correlated with Disjunct Core Area Standard Deviation (CASD), suggesting that bird density index was higher in regions with less variation in the sizes of the core areas when each core area within each patch was assessed separately. Less significant were weak positive correlations between bird density index and patch diversity (SDI, MSIDI), evenness (SEI, MSIEI, SHEI), and Mean Nearest Neighbor (MNN), suggesting that density may also have been somewhat higher in areas divided relatively evenly into diverse cover classes and in which patches of the same class were repeated over short distances.

Although the variance in bird density index explained by the multivariable model was modest (21%), the model was highly significant ($p < 0.0001$). This finding indicates that at the spatial scale of the individual observation area, patch metrics were indeed predictive but did not explain a high proportion of variation in bird density index. This is consistent with the results of Stralberg et al. (2010) for the two different subspecies of song sparrows in the northern part of the estuary. Some of the variance not accounted for in the model is undoubtedly from natural variation only sparsely sampled by the eight visits to each observation area during the study period. Our model explained a similar amount of population variance as the three previous studies of abundance of the other subspecies of *M. melodia* in relation to salt marsh vegetation composition and configuration at the patch scale (Nur et al. 1997; Spautz et al. 2006; Stralberg et al. 2010), although we based our model on different metrics.

Nur et al. (1997) tested the relationship between northern estuary *M. melodia* abundance and the cover fraction of eight major plant species, the degree of local marsh channelization, the distance to the nearest water body, the type and width of channels, the number of surrounding levees, and the size and isolation of the marsh. They found that abundance was positively related to the degree of channeliza-

Example Set 1			Example Set 2		
	Site: Obs. Area: Density: MCAI: CACV1:	Ravenswood Slough #71 2.546 0.82 2407		Site: Obs. Area: Density: MCAI: CACV1:	Cogswell Marsh #1 0.878 1.05 1914
	Site: Obs. Area: Density: MCAI: CACV1:	Ravenswood Slough #73 5.093 1.07 2526		Site: Obs. Area: Density: MCAI: CACV1:	Jarvis Landing #22 3.737 1.46 1966
	Site: Obs. Area: Density: MCAI: CACV1:	Dumbarton Point #28 5.105 1.29 2675		Site: Obs. Area: Density: MCAI: CACV1:	Ravenswood Slough #70 3.820 1.45 2049
	Site: Obs. Area: Density: MCAI: CACV1:	Dumbarton Point #30 5.305 1.60 2771		Site: Obs. Area: Density: MCAI: CACV1:	Dumbarton Point #35 8.594 1.52 2361
	Site: Obs. Area: Density: MCAI: CACV1:	Dumbarton Point #41 7.639 1.60 2910		Site: Obs. Area: Density: MCAI: CACV1:	Ravenswood Slough #72 9.095 1.69 2459
	Site: Obs. Area: Density: MCAI: CACV1:	Dumbarton Point #39 7.878 1.95 2931			

Classification Legend:

🟦 water	🟧 *Spartina* spp. (mostly *Spartina foliosa*)
🟫 levees, wrack, structures, dark shadows	🟩 *Frankenia salina*, *Jaumea carnosa*, *Distichlis spicata*
▨ *Sarcocornia pacifica* (*Salicornia virginica*)	🟪 *Grindelia stricta* or *Bolboschoenus* (*Scirpus*) *maritimus*

Figure 3 Examples of classified surface cover in observation areas spanning the range of the bird density index (birds detected ha^{-1}) and of variations in MCAI and CACV1 metric values. The six observation areas within Example Set 1, at left, were selected as a set because they depicted marsh areas with similar cover patterns consisting of large *Sarcocornia* areas bisected by a linear levee or channel feature. The bird density index ("Density") associated with each of these similar marsh areas ranged from 2.546 to 7.878 birds detected ha^{-1}. Concurrently, the calculated values of MCAI (Mean Core Area Index) increased from 0.82 to 1.95 and of CACV1 (Patch Core Area Coefficient of Variation) from 2407 to 2931. In contrast, the five observation areas in Example Set 2 exhibited a wider variety of marsh cover patterns yet still demonstrated the positive relationships between bird density index ("Density") and MCAI or CACV1; these positive relationships were central to the main results of this study.

tion (R^2 = 0.376), total vegetation cover fraction, and the area of isolated marshes (but not of connected marshes) (Nur et al. 1997). They found that abundance was not conclusively tied to the cover fraction of individual vegetation species (Nur et al. 1997).

Spautz et al. (2006) tested the relationship between northern estuary *M. melodia* abundance and both within-marsh and marsh-scale variables. Within a marsh, they tested: plant species cover fractions, vegetation species height, richness, and diversity; the cover fractions of other types of surfaces (e.g., ponds, channels); local channel density and closest channel width. At the whole-marsh scale, they tested: proximity to other land cover types (e.g., upland, urban, water) and local proportions of those types, marsh size, nearest marsh neighbor distance, whole-marsh perimeter-to-area ratio, and fractal dimension. None of these metrics overlapped with those of this study. Within a marsh, Spautz et al. (2006) found that abundance was positively correlated with tall shrub cover (*Grindelia stricta* and *Bachharis pilularis*) and negatively correlated with pond, pan, and rush (*Juncus* spp.) cover (R^2 = 0.176). However, they also included metrics regarding landscape configuration at the whole-marsh scale and larger in their analysis which, in combination with patch metrics, improved model performance (R^2 = 0.188 for landscape scale only; R^2 = 0.322 for two-scale model).

Stralberg et al. (2010) tested the relationship between northern estuary *M. melodia* abundance and: marsh soil water salinity, average elevation, marsh age, levee proximity and channel proximity, channel density and channel area, normalized difference vegetation index (NDVI), Shannon vegetation diversity index, and the proportional cover of four major vegetation species. They found that abundance across all sites (without including a site variable, as in this study) was positively correlated with *Schoenoplectus acutus/californicus* cover, soil salinity, NDVI, *Lepidium latifolium* cover, channel proximity, and channel area and was negatively correlated with *Scirpus americanus* cover (R^2 = 0.401); their predictions were improved by inclusion of a site variable (R^2 = 0.543). Additionally, Stralberg et al. (2010) showed that a linear model, such as was used in this study, was most appropriate for their comparable data set for tidal marsh song sparrows in San Pablo and Suisun bays, among considerations of alternative generalized linear models.

Overall, we conclude that the sizes, shapes, and spatial configurations of vegetation patches in a salt marsh are as relevant to the definition of quality *M. m. pusillula* habitat as some aspects of marsh cover composition, channelization, and landscape context. This finding is significant for two reasons. First, it demonstrates the utility of marsh cover configuration metrics, irrespective of composition, for assessing habitat, which had not previously been extensively tested. Second, it provides a new method to help map potential habitats in a non-invasive manner, since these configuration-based metrics are easily computed from remote sensing imagery with minimal site visitation. In other words, this methodology could be implemented to predict suitable habitat using remote-sensing in other unsampled locations that may or may not be candidates for restoration. Also, this study lacked quantitative data on all the variables explored by the above-mentioned studies so we could not complete a thorough quantitative synthesis of composition and configuration metrics, combined; however, conclusions combining the results of this study and those by Stralberg et al. (2010) suggest such an analysis would be additionally promising beyond what has been achieved by the analyses so far.

Limitations of Data and Analysis

In this study, the vegetation pattern analysis was based on categorical maps derived from visual-spectrum aerial photography. The advantages of this approach included the non-invasive methodology and the low time and labor requirements of supervised classification. Qualitatively, the classified vegetation patches corresponded to patches distinguishable to the eye in the imagery. However, the pixel-level noise that commonly results from spectrally-based classification of very high resolution imagery produced some very small vegetation patches that gave the vegetation maps a noisy, speckled appearance in some areas. It is likely that many single-pixel patches included in the analysis were attributable to this common difficulty, although some may have reflected accurate classification of very small vegetation patches. Manual classification of features that were difficult to distinguish spectrally in this study, such as water bodies, was subject to interpretation, which can yield results that cannot be compared across space or time (Blaschke and Hay 2001; Burnett and Blaschke 2003; Tuxen and Kelly 2008). These reclassified polygons also lacked the noise present in the rest of the imagery. Post-classification smoothing of the vegetation maps (Townsend 1986; Stralberg et al. 2010) or object-based image analysis (Tuxen and Kelly 2008; Moffett and Gorelick 2013) in future studies might lessen inconsistencies in spatial analysis that might arise between areas that were classified automatically and manually.

Management and Restoration Implications

As a habitat assessment tool, the quantitative analysis of the configuration of salt marsh surface cover piloted in this study is promising because it is based on non-invasive remote sensing. It also requires minimal ground observation because overall vegetation patterns often exhibit high contrast in remote sensing imagery. In contrast, detailed mapping of vegetation composition requires extensive ground-based observations to characterize and validate the spectral signatures of each species. For this reason, more routine use of configuration-based metrics may realize time and cost savings in habitat assessments. As a restoration and monitoring tool, such remote sensing-based assessments could track the development of vegetation patterns on restoration sites. This tracking might provide early clues about wheher the site will develop vegetation patterns with characteristics suitable for *M. m. pusillula* or if it might develop simpler vegetation patterns less likely to support high densities of *M. m. pusillula* but perhaps suitable for other species of concern.

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