Response of Waterbird Communities to Habitat and Landscape Structure along an Urban Gradient in Phoenix, Arizona

by

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ABSTRACT

Urban riparian corridors have the capacity to maintain high levels of abundance and biodiversity. Additionally, urban rivers also offer environmental amenities and can be catalysts for social and economic revitalization in human communities. Despite its importance for both humans and wildlife, blue space in cities used by waterbirds has received relatively little focus in urban bird studies. My principal objective was to determine how urbanization and water availability affect waterbird biodiversity in an arid city. I surveyed 36 transects stratified across a gradient of urbanization and water availability along the Salt River, a LTER long-term study system located in Phoenix, Arizona. Water physiognomy (shape and size) was the largest factor in shaping the bird community. Connectivity was an important element for waterbird diversity, but not abundance. Urbanization had guild-specific effects on abundance but was not important for waterbird diversity. Habitat-level environmental characteristics were more important than land use on waterbird abundance, as well as diversity. Diving and fish-eating birds were positively associated with large open bodies of water, whereas dabbling ducks, wading birds, and marsh species favored areas with large amounts of shoreline and emergent vegetation. My study supports that Phoenix blue space offers an important subsidy to migrating waterbird communities; while alternative habitat is not a replacement, it is important to consider as part of the larger conservation picture as traditional wetlands decline. Additionally, arid cities have the potential to support high levels of waterbird biodiversity, heterogeneous land use matrix can be advantageous in supporting regional diversity, and waterbirds are tolerant of urbanization if proper resources are provided via the habitat. The implications of this study are particularly relevant to urban planning in arid cities; Phoenix alone contains over 1,400 bodies of water, offering the opportunity to design and improve urban blue space to optimize potential habitat while providing public amenities.

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INTRODUCTION

United States urban populations increased by 12.1% from 2000 to 2010 (US Census 2012) and the majority of the world population now lives within urban areas (United Nations 2014). Furthermore, Seto et al. (2011) found that area of urbanization doubled between 1970 and 2000; and by 2030, urbanized land cover is predicted to triple from the area in 2000. This growth will cause urbanization to further encroach on protected areas by almost 1,000,000 km^2 (Guneralp and Seto 2013). One of the fastest growing cities in the United States is The Phoenix Metropolitan Area, which has an estimated population of over 4.4 million as of April 2014 and a growth rate of 4% per year in the last 40 years (US Census 2015).

Land-use change associated with urban growth often results in the reallocation of water resources to supply environmental amenities valued by residents (Larson and Perrings 2013). In the arid Southwest, water is frequently diverted to provide public amenities within cities (Grimm and Redman 2004). The importance of water resources for urbanized areas is not a novel development. In Phoenix, humans have been changing their habitat for thousands of years through the redistribution of water. A total of 34 prehistoric canals have been excavated and it is hypothesized that an estimated 500 miles of canals irrigated 110,000 acres within the Salt River basin between 450 and 1450 AD (Showalter 1993).

In arid cities, water provisioning can create green and blue space not typically found in desert ecosystems, such as golf courses and artificial lakes. Blue space can be defined as areas that offer aquatic based environmental and public amenities. Green and blue space within cities provides important resources for both humans and wildlife. Blue space has been shown to yield a number health benefits to human communities (Tzoulas et al. 2007). Waterfront walks are a preferable way to spend leisure time and give solitude from daily stress; use of waterfront areas have been tied to strong place attachment (Völker and Kistemann 2012). Aesthetically, water is considered to be a central landscape element (Kaplan and Kaplan 1989). Green and blue spaces also have positive effects on biodiversity in urban ecosystems. Ortega-Álvarez and MacGregor-Fors (2009) found that high bird evenness (relative abundance of species richness) and biodiversity could be preserved within cities as a response to localized green space. Similarly, riparian corridors in urbanized areas have the capacity to harbor high levels of abundance and biodiversity (Green and Baker 2003; O'neal and Rotenberry 2009).

Wildlife use of freshwater in cities can be used as an opportunity to enhance regional biodiversity through urban areas (Rosenzweig 2003); but, there is a lack of systematic tools to compare urban sites at various spatial and temporal scales to aid in decision making (Tallis and Polasky 2009). The spatial understanding of biodiversity within cities will enhance integration with other ecosystem services to give a clearer idea of what is happening at a specific area and allow for thorough investigation of potential tradeoffs. For example, shallow wetland depth and large surface area are positively related to waterbird biodiversity and nitrogen retention; but then also reduce the efficiency for phosphorus retention (Hansson et al. 2005).

My study concentrates on waterbird communities' use of blue space in Phoenix, Arizona. Waterbirds are charismatic taxa that offer a range of benefits, including recreational revenue and improved ecosystem functioning. Despite this, global waterbird populations are in decline. Habitat loss (Dynesius and Nilsson 1994) has adversely affected waterbirds; for example, 70% of riparian forests in the United States have been converted for various anthropogenic purposes (Mac 2000). Engineered aquatic habitat has been shown to provide supplemental habitat for waterbirds and can help mitigate habitat loss and degradation. However, there is a paucity of studies looking at waterbird communities within urbanized areas, especially in arid regions.

The central research objective connecting my thesis focuses on how community components of waterbirds vary along a gradient of urbanization and water availability in an arid city. I address several interrelated topics of waterbird communities' habitat associations and spatial distributions within in an urban ecosystem. Chapter 2 explains the relationship among habitat variables that are important for waterbirds throughout the Salt River. I determine how community assemblage, relative abundance, and biodiversity are affected by the biophysical factors. Chapter 3 extends this research into applications for spatially modeling macro-ecological trends in an urban environment. By understanding how to define and predict biodiversity distribution throughout an urban mosaic, we can incorporate the success of biotic communities with other important ecosystem services to optimize blue spaces at the intersection of human communities and urban wildlife.

CHAPTER 2

WATERBIRD COMMUNITY COMPOSITION, ABUNDANCE, AND DIVERSITY IN AN ARID CITY

INTRODUCTION

As of 2010, 80.7% of the United States' population lives in urban areas (US Census 2012) and by 2050 the world urban population is projected to grow by 2.5 billion people (United Nations 2014). Between 1950 and 2000, the continuous United States' urban land expanse nearly doubled in size to reach a total area of 74,242 million km^2 (Seto et al. 2011). Cities continue to expand outward, urban and exurban settlement covers four to five times the area as it did in 1950 (Brown et al. 2005). The rapid expansion of urbanization calls for a better understanding of how biodiversity in urban environments is influenced by decisions that affect habitat characteristics (Hosteler and Knowles-Yanez 2003).

Urban research has highlighted key biodiversity trends that span numerous taxa and geographical locations. As a whole, cities generally have a higher abundance for commensal groups of species and an overall decrease in diversity measures (McKinney 2008). This pattern has been documented in plant, arthropod, and herpetofauna communities. Bird abundance is higher and richness is lower in high density areas; avian richness often peaks in areas of intermediate urban density (e.g., Blair 1996; Melles et al. 2003). Land use within the urban matrix at various scales, available habitat, and socioeconomic variables can all impact urban biodiversity trends (Melles 2005; Lerman and Warren 2011).

Despite the numerous studies of urban bird biodiversity patterns, there is often a focus on terrestrial bird species. There is an overall paucity within the literature of community level analysis concerning the patterns of waterbird response to urbanization. Waterbird communities may respond differently to urbanization than terrestrial species due to their unique habitat and foraging requirements. Waterbirds are a diverse group of species closely associated with freshwater and marine habitats, and are important as both indicators for ecosystem health (Ogden et al. 2014) and as a source of recreational revenue. In a 2009 report released by the U.S Fish & Wildlife Service, 48 million people in the United States consider themselves active birders, generating over $11 billion in local, state, and federal tax revenue (Carver 2009). Out of the group of active birders, 77% reported observing waterfowl, making them the most watched type of bird (Carver 2009). Regardless of their importance, global waterbird populations are declining. Anthropogenic land-use change from water diversion has reduced and degraded habitat availability at stopover and wintering sites (Page and Gill 1994). However, in the arid Southwest, traditional views on the effects of habitat fragmentation may not apply to desert ecosystems. Skagen et al. (1998) illustrated that migrating birds have adapted to fragmented habitat availability in deserts and are opportunistic in their use of small habitat patches. Similarly, Flannery et al. (2004) and Patten (1998) also concluded that mesic strips of riparian habitats provide a stark contrast to an otherwise arid landscape, providing wintering and stopover sites for waterbirds, despite their size and isolation.

Cities within the arid Southwest often act as a mesic relief to the dry surrounding habitats, offering similar resources as the natural riparian strips waterbirds have traditionally been shown to use. In desert cities, waterbirds have the potential to use the large amount of aquatic resources provided by the reallocation and distribution of water. In Phoenix, the Arizona Game and Fish Department has been conducting a waterbird census since 2006 and determined that numerous urban water-bodies attract a proportionally higher diversity and abundance of waterbirds than anywhere else in Arizona (http://www.azfo.org/namc/IndexphoenixUrban.html). Another study completed in Florida found that waterbird guilds have a significantly higher than expected richness along developed shorelines compared to undeveloped habitat (Traut and Hostetler 2004).

Study Objectives

The purpose of my project is to link community parameters of migratory waterbirds to habitat characteristics and landscape structure to define and predict priority areas for conservation and restoration along the Salt River. Specifically, my research objectives are to:

1. Identify how environmental variables that are important to waterbirds shift along a gradient of urbanization and water availability.
2. Determine the relationship among habitat and landscape characteristics with waterbird community measurements including: guild abundance, community assemblage variation and structure, and diversity.

METHODS

Study Area

The Salt River is a once perennial river that forms from the confluence of the White and Black Rivers in the White Mountains, Arizona (33.4420, -112.1847) and stretches 200 miles throughout the Tonto National Forest and Phoenix Metropolitan Area to join the Gila River (33.2252, -112.1847). The river flows through the Theodore Roosevelt, Horse Mesa, Mormon Flat, and Stewart Mountain Dams. The Lower Salt River is diverted by the Granite Reef Diversion Dam into canals as part of the Salt River Project to provide drinking and irrigation water to Phoenix. The majority of the riverbed that passes through Phoenix is dry, with the exceptions of patchy ephemeral and a few specific perennial water sources. The result is a highly heterogeneous landscape with patchy habitat characteristics spread throughout the extent of the river. The surrounding matrix is equally heterogeneous, comprising national forest, desert, urban, and agricultural land types. My study focused on a 75-kilometer segment of the Salt River (Appendix I), starting at Saguaro Lake (33.5656, -111.5361) and ending at the Gila River confluence (33.3811, -112.3131).

Avifauna

I quantified the waterbird community during the winters of 2015 and 2016 (December-February) at 18 transects per winter for a total of n=36 transects (Appendix I). Transects were placed parallel to the water's edge, stratified along gradients of both extent of water availability and level of urbanization (urban, intermediate, and desert) at least 700 m apart. Surveys were conducted in the winter because that is when the majority of waterbirds migrate through the region. I used the line transect method (Bibby et al. 1992) to conduct waterbird community surveys and recorded waterbirds within 150 m of the transect center (sensu, Rathod and Padate 2007; Roy et al. 2011; DeLuca et al. 2008). Trained observers slowly walked transects to flush cryptic or hidden species and recorded any birds seen or heard within the truncation distance. Counts occurred within 4 hours of sunrise, with wind below 20 km per hour and precipitation no heavier than a light drizzle. Surveys were completed 3 times per winter season (Conway 2011). On repeat visits, the site order was rotated to reduce bias.

Community measurements of guild abundance and diversity were derived from bird surveys pooled over two years of sampling because there was no significant difference between guild abundance or richness between the two years, and year-effects were not the focus of my study. Birds were classified into six guilds (dabbling ducks, diving ducks, fish-eating birds, rails, shorebirds, and wading birds) primarily based on bird foraging strategies and functional traits (Elphick and Dunning 2001; Appendix II). Prior to analysis, species abundance for each site was standardized by the area of water so that abundance data was interpreted as usage per available habitat, or the relative abundance. Guild abundance was calculated as the sum of total individuals per guild averaged over the three visits and log-transformed to normalize the data. I calculated species richness by summing total species detected on any one of the six surveys at each transect. I determined waterbird diversity by calculating two diversity indices: Shannon Diversity Index and Simpson Diversity Index (Hill 1973) at each site. I visualized the Renyi diversity profiles of sites grouped according to their position within level of urbanization and water availability (Hill 1973). The Renyi diversity profile is a visualization of biodiversity across multiple indices. Horizontal axis (H-alpha) represents discrete diversity indices that move from indices calculated with an emphasis on richness and evenness for lower values, higher axis values place an emphasis on abundance. If the H-alpha lines do not cross, biodiversity is higher despite what diversity index is selected. The 12 sites with highest levels of urbanization were placed into ‘urban’, followed by the next 12 being placed into ‘intermediate’ and the final 12 with the lowest levels of urbanization along the gradient were considered ‘desert’. This was repeated for the four levels of water availability.

Environmental Variables

For each transect, I quantified 20 environmental variables categorized as aquatic, terrestrial, or landscape (Table 1). The environmental variables characterized the extent of land cover type and other surface properties. Habitat measurements were made from aerial imagery obtained via Landsat 8 satellite data. The GIS analysis and data collection were performed in ArcMap 10.1 geographic information system (ESRI 2006) and identification and estimation of habitat measurements were verified in the field for each transect.

Eleven of the environmental variables were derived from a land cover classification: area, edge ratio, connectivity, isolation, canopy cover, distance to desert, cultivated vegetation, urban, riparian vegetation, water availability, and distance to agriculture. I performed a supervised land cover classification with ERDAS Image software (2006) based on the Landsat 8 Satellite imagery, with 11 bands and a 30 m resolution, acquired in February 2015. Supervised classification consists of user selection of representative samples for each land cover class, known as ‘training sites’; the spectral signatures of the training sites are then used to determine the land cover class for each raster cell by pattern matching. The land cover classification model for the signature file included seven categories: urban disturbed (residential, industrial, and commercial land use), cultivated vegetation (agriculture, irrigated grass, golf courses, and mesic yards), riparian vegetation, impervious surface, water, river gravel/ bare ground, and undisturbed (desert, desert shrub, urban desert remnant parks). A maximum-likelihood classification was employed using the signature file to run the land use classification on the extent of the study area. The land cover classes were reclassified into separate rasters. The water classification raster was converted to polygons and combined with a shapefile mapping artificial lakes in Phoenix (Larson and Grimm 2012).

To quantify the seven aquatic and six terrestrial variables, I collected habitat data from the land cover classification and the unclassified imagery within 150 m on either side transect, encompassing a total area of 225 m x 300 m. Similar to Germaine et al. (1998) and Lerman and Warren (2011), I chose a habitat plot width two times that of my bird sampling transect to appropriately characterize vegetation and aquatic variables.

Seven variables were collected using a dot-grid overlay on the unclassified Landsat imagery from February 2015. Emergent vegetation, open water, cobblestone, impervious surface, bare ground, tree cover, and shrub cover were calculated as percentages for each site, where 100 random points were placed on the 225 m x 300 m transect area using the ‘Generate Random Points’ tool and each point was categorized into one of the seven variables.

Three aquatic variables were measured using the ‘water’ land cover classification raster converted into a polygon shapefile. I defined connectivity as the distance to the next closest water polygon (km). Higher values denote lower levels of connectedness as the distance between water increases. Area and edge ratio were collected via the water polygons delimiting each body of water. Area was defined as the total area of the water polygon where each transect was located (hectare). The edge ratio describes the shape of the body of water and was defined as the amount of perimeter (km) per area of water (hectare). Higher edge ratio describes bodies of water with complex shoreline and maximized perimeter per area of water, smaller values would describe large, round bodies of water.

Perching structure was the sole variable derived from direct field observations, each transect was assigned as a categorical value from 1-36, with 1 representing transects with the lowest available amount of perches available. Perching structure included concrete pillars, vertical vegetation, or buoys.

Two additional terrestrial characteristics were collected to further explain the vegetation characteristics of each transect. I calculated canopy cover as the percentage of riparian vegetation class present within each transect using the land cover map. Additionally, I calculated the normalized difference vegetation index, or NDVI, (NIR - Band 4/ NIR + Band 4) from the unclassified imagery as a measure of greenness.

Seven landscape characteristics in total were collected using the land cover classification to describe the heterogeneous matrix surrounding the riparian area. For landscape-level variables, I laid a 1.5 km buffer around the center point of each transect to quantify surrounding land cover type and urban gradient distance measurements. I collected two distance measurements: distance to desert (km) and distance to agriculture (km) by measuring the distance from the transect center to the closest habitat patch for each respective land cover class. Cultivated vegetation, urban disturbed, riparian vegetation, and water availability were collected by averaging the number of cells within each 1.5 km buffer around the transect. I defined the isolation ratio for each transect as the ratio of the area of water in proportion to the area of urbanization and impervious surface. Higher isolation ratio values describe a large amount of water available on a landscape-level scale, smaller values describe smaller water bodies interspersed throughout urban land use.

Statistical Analysis

I reduced the variation and multicollinearity in the environmental variables using a Principal Component Analysis (PCA). I employed a correlation matrix for each group of environmental variables: aquatic, terrestrial, and landscape (R, Package Vegan). Prior to PCA analysis, I calculated a Pearson Product-Moment Correlation Coefficient for the 20 environmental variables to determine how the variables were related to one another (Table 1). Seven variables went into the aquatic PCA (extent, perching, open water, connectivity, cobblestone, emergent vegetation, and edge ratio), six variables comprised the terrestrial PCA (canopy cover, tree, shrub, bare ground, impervious surface, and NDVI), and seven variables were incorporated into the landscape PCA (distance to desert, cultivated vegetation, disturbed land use, distance to agriculture, riparian vegetation, water, and isolation). I scaled and centered environmental data as an input for the PCA because variables were measured in varying units. Components with an eigenvalue >1 were selected for each of the three variable groups (Kaiser 1960). I then interpreted the components produced from the relationship between variables and factor loadings within each component. Variables with the largest scores for each component had a larger weight when defining its characteristics (Legendre and Legendre 1998). I generated a biplot of the first two components for each PCA to display variable loading on components in relationship to one another.

To determine how aquatic, terrestrial, and landscape factors affected waterbird community assemblage across my sites, I used a Redundancy Analysis (RDA). This ordination technique determines the relationship between species distributions patterns in site space and depicts the variation in the bird community that is constrained by the environmental attributes (ter Braak 1986). I used Redundancy Analysis rather than Canonical Correspondence Analysis because the axis length was 2<. Prior to analysis, I verified that the PCA components for each environmental matrix (aquatic, terrestrial, and landscape) did not exhibit multicollinearity. Because ordination analysis preforms poorly with the inclusion of rare species, I eliminated species found at fewer than 10% of sites (McCune and Grace 2002).

I tested the overall significance for the three RDAs, each axis, and the environmental component used in the analysis using a Monte Carlo Global Permutation Test (Hope 1968). I calculated the total inertia of each RDA to explain the total variation in the community caused by aquatic, terrestrial, and landscape components. I calculated bi-plot scores of the environmental constraints and factor loading for each species, which I averaged and reported at the guild level, for the significant axis. I calculated the guild centroids in ordination space by averaging the position of the species belonging to each guild. I generated a plot for each RDA to display the ordination results and visually ascertain the relationship among waterbird community guilds and environmental variables.

I used Generalized Linear Models (GLM) to quantify the relationship and relative importance of the PCA components in predicting waterbird guild abundance and diversity (Nelder and Baker 1972). To determine which components to include in my model building, I first ran a simple regression for each independent variable (dabbler abundance, diver abundance, fish-eating abundance, shorebird abundance, rail abundance, shorebird abundance, wader abundance, diversity indices, and richness) against aquatic, terrestrial, and landscape components. Components with a correlation below 0.25 were omitted from the GLMs to remove confounding effects of weakly associated variables. To further reduce multicollinearity, if two components had a Variance Inflation Factor (VIF) > 2.50, the component with the higher correlation to the independent variable was kept in the model. All possible combinations of components for each model were considered in the ranking system. I ranked the GLMs for guild abundance and diversity (Burnham & Anderson 2004) using ΔAICi scores. I reported the two 'best fit' models for each independent variable, where the top model had a ΔAICi=0, as well as the directionality of the relationship (negative or positive) of the component within the top-preforming models.

RESULTS

A total of 51 species of waterbirds were observed over the course of my study, encompassing 2679 individuals, with a maximum of 327 individuals per transect (Table 2). Richness at sites ranged from 1 to 29 species. The maximum number of individuals (abundance) and richness were observed at the Tres Rios Wetlands (33.389402, -112.2597653). Fish-eating birds and dabbling ducks had the highest number of species observed within a guild and rails had highest average abundance per species, with American Coot (*Fulica americana*) comprising 88.8% of the guild. American Coots were the most abundant species observed throughout the study. Rare species observed included cryptic marsh birds such as: *Ixobrychus exilis* (Least Bittern), *Rallus obsoletus* (Ridgway's Rail), and *Porzana carolina* (Sora); the low number of observations for this group may partly be attributed to the lack of playback calls conducted during the survey period. Rare species such as *Dendrocygna autumnalis* (Black-Bellied Whistling Duck) were also observed over the course of the survey. Rare species were primarily found in areas of intermediate urban land use.

The Renyi Diversity Index showed larger water bodies with more emergent vegetation consistently exhibited higher diversity than large open sites. Diversity then decreased with smaller, dry sites (Figure 1). Likewise, intermediate levels of urbanization also displayed the highest levels of diversity, but by a closer margin then the gradient of water. However, diversity across levels of urbanization is variable depending on the amount of water available (Figure 2). In wetter sites, urban and intermediate land use were associated with higher H-alpha values, this trend was reversed at drier areas (Figure 2a vs. 2b).

Environmental Variable Associations

The three PCA analyses reduced 20 environmental variables into eight components explaining aquatic, terrestrial, and landscape level characteristics of the Salt River (Table 3).

Eight environmental variables were included in the aquatic PCA, the first three components (A1, A2, A3) accounted for 81.6% of the environmental variation of aquatic habitat-level characteristics. Sites with high component A1 scores can be described by large areas of open water with an ample amount of artificial structures to perch on, whereas low A1 scores describe habitat that has a smaller amount of water availability and is overall drier (Table 4). Sites with high A2 scores were defined by shoreline complexity and emergent vegetation (Table 4). Component A3 described connectivity, or the distances separating water resources along the river. Sites with high A3 scores would exhibit high connectivity and cobblestone (Table 4). In the absence of water on the river bottom, cobblestone is the most common ground cover.

The terrestrial PCA reduced six variables into two components explaining 69.9% of the variation in environmental variables describing vegetation and ground cover (Table 4). Areas with high T1 values had high vegetation and canopy cover and low amounts of impervious surface. T1 was correlated to component A2 ($r = -0.62$). This is opposed to high T2 scores, which indicated areas with bare ground and sparse shrub cover surrounding the shoreline, resulting in lower NDVI values (Table 4).

The landscape PCA reduced seven variables into three components explaining 84.0% of the variability present in the landscape surrounding the surveyed riparian areas (L1, L2, and L3, Table 3). Component L1 represents a gradient from desert habitat (high scores) to highly urbanized habitat (low scores). High component L2 scores corresponded to areas in Phoenix located in intermediate disturbance zones, close to adjacent agriculture fields and cultivated vegetation (Table 4). High L3 scores were interpreted as sites with a large amount of water available at the landscape-level (1.5 km) scale.

Community Variation

All three RDAs (aquatic, terrestrial, and landscape) explained the proportion of waterbird community variation greater than expected by chance ($F_{3, 32} = 4.65$, $P < 0.001$; $F_{2, 33} = 3.60$, $P < 0.001$; $F_{3, 32} = 3.50$, $P < 0.001$). The first two axes of the aquatic ($F_{1, 32} = 10.62$, $P < 0.001$; $F_{1, 32} = 2.60$, $P < 0.002$; Figure 3) and landscape ($F_{1, 32} = 5.46$, $P < 0.001$; $F_{1, 32} = 4.19$, $P < 0.001$; Figure 4) ordinations were significant, whereas only the first axis of the terrestrial ordination was significant ($F_{1, 33} = 6.23$, $P < 0.001$; Figure 5). In total, the aquatic, terrestrial, and landscape components explained 73% of the variation of the waterbird community in Phoenix, Arizona along the Salt River. The suite of species I observed at each site was influenced by both habitat-level (aquatic and terrestrial ordinations) and landscape-level components. Overall, the habitat-level aquatic variables explained the largest percentage of the variation in the waterbird community (30.4%), followed by landscape (24.7%), and terrestrial constraints (17.9%).

There was a strong gradient of water availability at the habitat-level represented along the RDA1 axis of the aquatic ordination driven by the A1 component. Extent and openness of water in a site (A1 values) decreased as you move from low to high RDA1 axis values. RDA2 denoted a gradient of shoreline complexity, emergent vegetation and connectivity; whereas low axis values correspond to high A2 and A3 component scores. Increasing RDA2 axis values shifts from sites with low levels of emergent vegetation and connectivity into more complex areas with a dominant shoreline, providing more shallows and vegetation access along the edge. When moving counter-clockwise along the four quadrants of the ordination: the upper left corner includes wet vegetated sites with complex shoreline, the lower left hand corner includes large, open sites, and the bottom right hand corner is composed of drier, cobble habitat lacking emergent vegetation (Figure 3). All three aquatic components were significant in the aquatic ordination for explaining waterbird community assemblage patterns ($F_{1,32} = 9.62$, $P < 0.001$; $F_{1,32} = 2.32$, $P < 0.022$; $F_{1,32} = 2.02$, $P < 0.044$; Figure 3), respectively. The A1 vector explained the community variation constrained by extent of water, and was tightly aligned with birds that dive for their food versus other foraging behavior. Diving ducks and fish-eating birds concentrated at areas that corresponded to low A1 vector values, indicating association with large, open bodies of water (Table 5). Rails, wading birds, and dabbling ducks fell at the high end of the RDA2 gradient and were associated with more complex, vegetated shoreline (Table 5). The mean position of shorebirds were found at high values of RDA1 and differed the most from the other guilds along the aquatic ordination (Table 5).

The variation in the waterbird community in Phoenix, Arizona was also defined by landscape-level factors. RDA1 corresponded to water availability; lower RDA1 axis values were associated with sites that have a higher concentration of water within 1.5 km of the site (Figure 4). Low RDA2 axis values represented desert sites and higher RDA2 values represented anthropogenic land use characterized by urban and agricultural sites with cultivated vegetation. Water availability ($F_{1, 32} = 4.90$, $P < 0.001$; vector L3 in Figure 4) was the primary component that explained community assemblage patterns, as well as agricultural land use ($F_{1, 32} = 3.04$, $P < 0.006$; L2 in Figure 4) and level of urbanization ($F_{1, 32} = 2.56$, $P < 0.013$; L1 in Figure 4). Fish-eating birds and dabbling ducks were associated with higher levels of urbanization; fish-eating bird abundance also followed a gradient of landscape-level water availability (Table 5). Conversely, diving ducks were negatively related to urbanization; but were found in similar aquatic microhabitats as fish-eating birds (chiefly driven by vector A1 from the aquatic ordination) and exhibited a similar association to landscape-level water availability (Table 5). Rails, dabbling ducks, wading birds, and finally shorebirds were also organized along the RDA1-axis in relation to water availability (Table 5).

The terrestrial ordination was the least powerful in terms of describing community composition (Figure 5). From negative to positive axis values, RDA1 was correlated with the decrease of NDVI and canopy cover, and an increase of bare ground.

The terrestrial ordination separated diving ducks and fish-eating birds from dabbling ducks, rails, shorebirds, and wading birds in association with terrestrial vegetation (Table 5).

Linking waterbirds and their environment

Environmental models explained guild abundance and diversity indices (Table 6). Dabbling ducks were associated with complex shoreline and emergent vegetation (A2) dominating the littoral zone, as well as urbanization (L1) and agricultural land use (L2; Table 6). The best-fit model for dabbling ducks included components A1 and L1 (r^2 = 0.32, $F_{2, 33}$ = 9.30, $P < 0.0006$). Diving ducks are the only guild negatively associated with urbanized areas and avoided sites associated with cultivated vegetation (r^2 = 0.49, $F_{3, 32}$ = 12.23, $P < 0.0001$; Table 6). The prominent component that explained fish-eating bird abundance is the extent of water available at the habitat-level (A1; Table 6). The competitive model of fish-eating birds was comparable to diving ducks in terms of component A1, but had the opposite relationship to disturbance and was positively associated with urban areas (r^2 = 0.63, $F_{2, 33}$ = 31.03, $P < 0.0001$; Table 6). Raillidae species (primarily American Coots) were positively associated with agricultural areas, as well as emergent vegetation and localized water extent (r^2 = 0.23, $F_{2, 33}$ = 6.28, $P < 0.005$; Table 6). Shorebirds were the only guild to increase abundance with connectivity (A3; Table 6) and the best performing model also included water extent and level of urbanization (r^2 = 0.43, $F_{3, 32}$ = 9.72, $P < 0.0001$; Table 6). Wading birds were the sole guild positively associated with vertical terrestrial vegetation and the top ranked model indicated a positive association with agriculture and emergent vegetation that provide foraging resources (r^2 = 0.43, $F_{3, 32}$ = 9.72, $P < 0.0001$; Table 6).

Diversity indices also indicated that the amount of water present at the habitat-level had a strong positive association with waterbird biodiversity (A1; Table 6). Connectivity was not a highly weighted variable explaining guild abundance, but was found in the top competitive models for diversity measures (A2; Table 6). Land use affected guild abundance (L1, L2, L3; Table 6), but not diversity. Habitat-level aquatic variables explained both guild abundance and diversity (A1, A2, A3; Table 6), connectivity increased in importance when predicting diversity (A3; Table 6). Terrestrial components were not relatively important for abundance; however, T2 was included in competitive models for two of the three diversity measures with a negative relationship (Table 6). Diversity indices were primarily driven by aquatic characteristics. The best fit models for the Shannon and Simpson diversity indices include all three aquatic components ($r^2 = 0.63$, $F_{3, 32} = 20.47$, $P < 0.0001$; $r^2 = 0.53$, $F_{3, 32} = 13.87$, $P < 0.0001$), respectively; the top Richness model included the first two aquatic components ($r^2 = 0.70$, $F_{2, 33} = 42.02$, $P < 0.0001$).

DISCUSSION

My study provides several insights into the links among habitat and landscape characteristics and waterbird community patterns in an arid city. Water shape and structure at the habitat-level was important for waterbird abundance and diversity. Interestingly, the intensity of urbanization and landscape-level water were less important for predicting diversity.

Waterbird abundance patterns observed in my study were similar to those identified in other studies of urban ecosystems. Urban land use had overall positive effects on waterbird abundance; but this pattern was guild-specific. A common artifact of urbanization on biotic communities is the overall increase in abundance (Shochat 2004; Chace and Walsh 2006). This has also been observed in other studies explicitly focused on waterbird abundance. Traut and Hostetler (2004) found that species abundance increased with shoreline development and in Portugal; variables related to human disturbance were positively associated with the abundance of four of the seven waterbird species observed in the study (Rosa et al. 2003).

Waterbirds used urban water in Phoenix, despite small size and lack of a continuous riparian area. Pearce (2007) hypothesized adjacent wetlands, or ‘clusters’, can act similar to larger wetlands in urban landscapes. Similarly, I found abundance was higher in urban and agricultural land use for all guilds except diving ducks and shorebirds. In Australia, both Raillidae species and diving ducks are negatively impacted by urbanization (Murray et al. 2013). However, Murray et al. (2013), asserted human access may be a driver for the relationship between diving ducks and habitat usage in urban areas, but this is likely not the case for rails. Therefore, the influence of urbanization may be context dependent due to interacting factors such as the amount of emergent vegetation present or water surface area.

Additional studies have pointed to the opposite trend of anthropogenic development near urban lakes and estuaries having negative impacts on waterbird communities (Rajashekara and Venkatesha; DeLuca 2004; Zydelis and Kontautas 2008). In Phoenix, however, water resources are redistributed throughout the city, resulting in an overall increase in water when compared to the outlying desert. The land-use change within Phoenix has transformed a perennial river with a concentrated amount of water and increased the total water area and permanence when compared to the surrounding desert. This study indicates the change of water resources in Phoenix has increased both the total habitat and suitability of the available habitat for waterbirds; resulting in large, diverse communities.

Water area is an important driver of waterbird abundance and diversity (Froneman et al. 2001; Rosa et al. 2003; Sánchez-Zapata et al. 2005). The increase of water in Phoenix may offset some of the potential negative effects of anthropogenic pressure. For example, dry urban areas had lower levels of biodiversity when compared to the desert; however, when water was abundant, urbanized areas had much higher levels of diversity. Indeed, extent of water was also the best predictor for guild abundance and was included in all but two of the best-fit models. Even when accounting for the size of water (as simple abundance would be expected to increase with water area), large bodies of water were still more important per area. Fish-eating birds, diving ducks, and rails all favored large, open bodies of water, shorebirds were found in smaller wetlands of shallow water over cobblestone.

Overall, habitat-level aquatic features were more important than landscape-level variables; indicating that waterbirds were responding to fine-scale habitat availability in Phoenix. Landscape-level water availability and vegetation in the landscape surrounding a body of water was relatively unimportant in determining waterbird abundance or diversity. Similarly, distance to the closest body of water was also unsubstantial in the guild abundance models, but drastically increased in importance for diversity measures.

Waterbird guilds responded individually to environmental components in addition to water and urbanization. Other substantial components that were related to guild abundance included: the amount of emergent vegetation, cultivated vegetation, and, to a lesser degree, ground cover. This group of components provide habitat provisioning that is uniquely required for the variety of foraging strategies exhibited by the waterbird guilds. The ratio of shoreline per surface area has also been shown to support waterbird communities. Dabbling ducks, rails, and wading birds were positively related to the complexity of the shoreline and amount of emergent vegetation present. Terrestrial components were the least important for both abundance and diversity, with wading birds having the only positive association with terrestrial vegetation surrounding the shore. Likewise, Murray et al. (2013) found no relationship between a ‘buffer zone’ (vegetated perimeter greater then 50m), and the density of any waterbird species or guild. Similarly, terrestrial factors along the Salt River did not contribute to variation in the community. This is interesting because planting vegetation is a common practice to enhance wetland habitat for waterbirds (Sharma and Saini 2012). Guild-specific responses demonstrated the complexity of the system and the importance of habitat heterogeneity.

Divergence in Waterbird Diversity Trends

Urbanization typically decreases richness (McKinney 2008) and diversity (Pillsbury and Miller 2008) across multiple taxa, such as birds (Anderies et al. 2007) and herpetofauna (Banville and Bateman 2012). However, in this study urbanization was a poor predictor of waterbird diversity across multiple indices. This appears to be a common trend emerging in urban waterbird research. Traut and Hostetler (2004) also found that species richness was not negatively impacted by shoreline development in a less arid environment (Florida) and Rosa et al. (2003) found water physiognomy had the largest effect on richness in Portugal. They suggest that species richness decreases when urbanization encroaches on the wetland, narrowing the width or changing the structure. In Phoenix, the largest emphasis was placed on aquatic characteristics for driving waterbird diversity. All three water components were found in the top competing diversity models. Surprisingly, landscape-level water availability was unimportant for waterbird diversity. Habitat-level water characteristics, the aquatic components, were much more important than landscape-level water. This may help explain why Phoenix's discrete blue spaces are able to support such high levels diversity and abundance.

Management Implications

Loss of freshwater habitat is a concern for global biodiversity and has the potential to cause waterbird population declines. However, urban water bodies have been shown to provide adequate alternative habitat with the capacity to support biodiversity. The presence and construction of lakes and wetlands in urban environments is important for biodiversity conservation as urban areas continue to expand and natural wetlands decline (Zedler 2000). Waterbird conservation seems to be an unintended consequence of many urban wetlands. Phoenix alone contains over 1,400 urban lakes, as well as areas of stormwater drainages, gravel pits, and treatment ponds that provide recreational areas or other public amenities as part of the urban infrastructure (Larson and Grimm 2012). However, here I show that waterbirds are taking advantage of the water in Phoenix, and that the heterogeneous land use matrix can be beneficial for supporting regional diversity by supporting a variety of species.

My study suggests that urban water in Phoenix is providing an important subsidy for migrating waterbird communities. Areas such as the Tres Rios Wetlands, constructed wetlands for wastewater treatment, and the Rio Salado Restoration Area, a green space with hiking and recreational opportunities, are both excellent examples of how water resources along the Salt River can serve both the community and urban wildlife. It is interesting to consider some of the potential outcomes if the “leakiness” of stormdrains are improved or the amount of public water is reduced (Chocat et al. 2007; Archibold 2007). As water conservation becomes increasingly important (Hirschboeck and Meko 2005), there must be awareness that water is a multi-faceted resource with the potential to optimize habitat and support biodiversity in addition to providing public services (Ignatieva 2010; Hansson et al. 2005).

TABLE 1. Descriptive statistics and sampling methodology of 20 environmental variables measured at 36 transects located along the Salt River in Phoenix Arizona between the winters (December- February) of 2015 and 2016.

Environmental Variables	Mean (± SE)	Correlations	Collection Method
Aquatic			
Emergent Vegetation (%)	15.89 (± 2.34)	-	Number of 100 points that were emergent vegetation
Open Water (%)	26.56 (± 3.63)	Extent (*r*=0.88), Cobblestone (*r*=-0.69), Perching (*r*=0.70)	Number of 100 points that were open water
Cobblestone (%)	10.61 (± 2.27)	Open Water (*r*=-0.69),	Number of 100 points that were cobblestone
Extent (hec)	21.90 (± 5.19)	Open Water (*r*=-0.88), Perching (*r*=0.73), Water (*r*=0.70)	Total area of surrounding body of water (hectare)
Connectivity (m)	197.67 (± 33.69)	Distance to desert (*r*=-0.74), Disturbed (*r*=0.73)	Distance to next closest body of water (m)
Edge ratio (km/hec)	0.43 (± 0.06)	Tree (*r*=0.67)	Perimeter of shoreline (km) per area water (hectare)
Perching Structure	6.81 (± 0.95)	Open Water (*r*=0.70), Extent (*r*=0.73)	Rank index (scale of 36) of artificial and natural perching structures available in the water
Isolation Ratio	18.70 (± 11.40)	-	Urban Disturbed/ Water Area per1.5 km
Terrestrial			
Impervious surfaces (%)	12.50 (± 1.77)	Tree (*r*=-0.70), Distance to desert (*r*=0.66)	Number of 100 points that were imperious surface
Bare ground (%)	15.00 (± 2.16)	-	Number of 100 points that were bare ground or gravel
Canopy Cover (%)	15.15 (± 2.37)	Tree (*r*=0.82), Riparian Vegetation (*r*=0.78)	Average vegetation class cover of transect using zonal statistics tool
NDVI (INT)	136.87 (± 1.33)	Riparian Vegetation (*r*=0.78)	Average NDVI (INT) of transect collected using zonal statistics tool
Tree (%)	9.89 (± 1.14)	Edge (*r*=0.67), Impervious surface (*r*=-0.70), Canopy Cover (*r*=0.82), Riparian Vegetation (*r*=0.78)	Number of 100 points that were tree cover
Shrub (%)	9.56 (± 1.01)	-	Number of 100 points that were shrub cover
Landscape			
Distance to desert (m)	3573.10 (± 660.10)	Connectivity (*r*=-0.74), Impervious Surface (*r*=0.67), Disturbed (*r*=0.92)	Distance to closest continuous (>2000 m^2) desert patch
Cultivated Vegetation (%)	12.07 (± 2.04)	Distance to agriculture (*r*=-0.93)	% Agriculture and grass classes in 1.5 km buffer
Urban Disturbed (%)	15.23 (± 2.83)	Connectivity (*r*=-0.74), Distance to desert (*r*=-0.92)	% Urban and impervious surface classes in 1.5 km buffer
Riparian Vegetation (%)	24.51 (± 3.37)	Tree (*r*=072), Canopy Cover (*r*=0.78), NDVI (*r*=0.75)	% Vegetation class in 1.5 km buffer
Water (%)	6.39 (± 1.24)	Extent (*r*=*0*.70)	% Water in 1.5 km buffer
Distance to agriculture (m)	5326.15 (± 956.90)	Cultivated Veg (*r*=-0.92)	Distance to closest agricultural field (m)

TABLE 2. Descriptive statistics of bird guilds per site observed at 36 transects along the Salt River in Phoenix Arizona between the winters (December- February) of 2015 and 2016. Transects were placed along a gradient of water availability and urbanization. Species were assigned to foraging guilds according to (Elphick and Dunning 2001). Species is the number of unique species observed within the guild. Mean abundance is defined as the total number of individuals observed per site.

Guild	Species	Total	Mean	Stdev	SE	Range	
						Min	Max
Dabbler	11	564	15.66	25.98	4.33	0	111
Diver	8	542	15.05	24.27	4.04	0	80
Fish-eating	11	489	13.58	20.97	3.50	0	77
Rail	5	618	17.16	20.27	3.40	0	82
Shorebird	10	169	4.69	6.35	1.06	0	22
Wading	7	235	6.52	8.64	1.44	0	32

TABLE 3. Results from separate Principal component analysis (PCA) of 20 environmental variables, organized into three predefined groups describing aquatic, terrestrial, and landscape characteristics (defined in Table x) along 36 Salt River transects in Phoenix, Arizona. Data were centered and scaled to account for different units. Components with an eigenvalue <1 were omitted from further analysis. Variables with the highest loading for the component are bolded.

Aquatic PCA			
	A1	A2	A3
Extent	**-0.53**	0.08	0.10
Open Water	**-0.53**	-0.04	0.21
Perching	**-0.43**	-0.13	-0.15
Emergent Vegetation	0.08	**-0.64**	-0.39
Edge	0.31	**-0.51**	0.15
Connectivity	0.17	0.49	**-0.67**
Cobblestone	0.35	0.25	**0.55**
Variation Explained (%)	43.5	23.0	14.3
Eigen Value	3.0	1.7	1.0
Terrestrial PCA			
	T1	T2	
Tree	**0.49**	0.08	
Impervious Surface	**-0.47**	0.01	
Canopy Cover	**0.45**	0.18	
Shrub	0.32	**0.66**	
Bare Ground	-0.30	**0.61**	
NDVI	0.38	**-0.39**	
Variation Explained (%)	52.9	17.0	
Eigen Value	3.2	1.0	
Landscape PCA			
	L1	L2	L3
Urban/ Disturbed	**-0.54**	0.18	0.13
Distance to Desert	**-0.54**	0.10	-0.04
Cultivated Vegetation	-0.21	**-0.53**	-0.45
Distance to Agriculture	0.39	**0.51**	0.12
Riparian Vegetation	0.37	**-0.45**	0.33
Water Availability	0.14	0.40	**-0.65**
Isolation	-0.25	0.20	**0.47**
Variation Explained (%)	40.9	24.7	18.4
Eigen Value	3.2	1.7	1.3

TABLE 4. Interpretation of PCA components based on the variables with the highest loadings in each component and correlation analysis to describe habitat characteristics of the Salt River, Phoenix, Arizona.

Component	Type	Description
A1	Aquatic	Extent, and openness of water
A2	Aquatic	Shoreline complexity and aquatic vegetation
A3	Aquatic	Habitat isolation and cobblestone percent
T1	Terrestrial	Canopy cover
T2	Terrestrial	Ground and shrub cover
L1	Landscape	Desert to urban gradient
L2	Landscape	Agriculture and cultivated vegetation levels
L3	Landscape	Landscape level water availability

TABLE 5. Centroid of six waterbird guilds, average ordinational position and standard error of species. Relative guild positions were used as part of the ordination interpretation to determine how each guild was constrained by the environmental components in Phoenix, Arizona.

RDA of aquatic components	RDA1	RDA2
Dabbler	-0.38 ± 0.12	0.16 ± 0.04
Diver	-0.53 ± 0.09	-0.27 ± 0.09
Fish-eating	-0.38 ± 0.16	-0.03 ± 0.06
Rail	-0.26 ± 0.08	0.12 ± 0.04
Shorebird	0.10 ± 0.10	-0.04 ± 0.08
Wading	-0.11 ± 0.04	0.18 ± 0.02

RDA of Terrestrial	RDA1	RDA2
Dabbler	-0.27 ± 0.13	
Diver	0.26 ± 0.08	
Fish-eating	0.32 ± 0.16	
Rail	0.11 ± 0.03	
Shorebird	0.03 ± 0.07	
Wading	0.01 ± 0.04	

RDA of Landscape Components	RDA1	RDA2
Dabbler	-0.04 ± 0.05	0.25 ± 0.10
Diver	-0.60 ± 0.18	-0.11 ± 0.11
Fish-eating	-0.15 ± 0.08	0.20 ± 0.11
Rail	-0.09 ± 0.07	0.13 ± 0.02
Shorebird	0.08 ± 0.03	0.11 ± 0.05
Wading	0.05 ± 0.02	0.12 ± 0.04

TABLE 6. Importance of environmental components in predicting guild abundance of waterbirds in Phoenix, Arizona using multi-model inference. Top two competing models are given. Component relationships represent the directionality of the beta estimate in the top preforming models.

Guild	Model	AIC	Likelihood	ω	Component Relationship							
					A1	A2	A3	T1	T2	L1	L2	L3
Dabbler	A2+L1	-127.76	1.00	0.36		-				-	-	
	A2+L1+L2	-127.45	0.86	0.31								
Diver	A1+L1+L2	-118.01	1.00	0.41	-					+	+	
	A1+L1	-117.24	0.68	0.28								
Fish	A1+L1	-168.97	1.00	0.43	-					-		+
	A1+L1+L3	-168.02	0.62	0.27								
Rail	A1+A2	-82.32	1.00	0.49	-	-						
	A1	-80.48	0.40	0.20								
Shore	A1+A3+L1	-159.97	1.00	0.64	+		+			+		
	A1+A3	-158.70	0.53	0.34								
Wade	A2+L2	-151.88	1.00	0.48		-			-		-	
	A2+T2+L2	-150.12	0.42	0.20								
Shannon	A1+A2+A3	44.20	1.00	0.55	-	-	+					
	A1+A3	44.65	0.80	0.44								
Richness	A1+A2	183.40	1.00	0.30	-	-	+					
	A1+A2+A3	184.29	0.64	0.19								

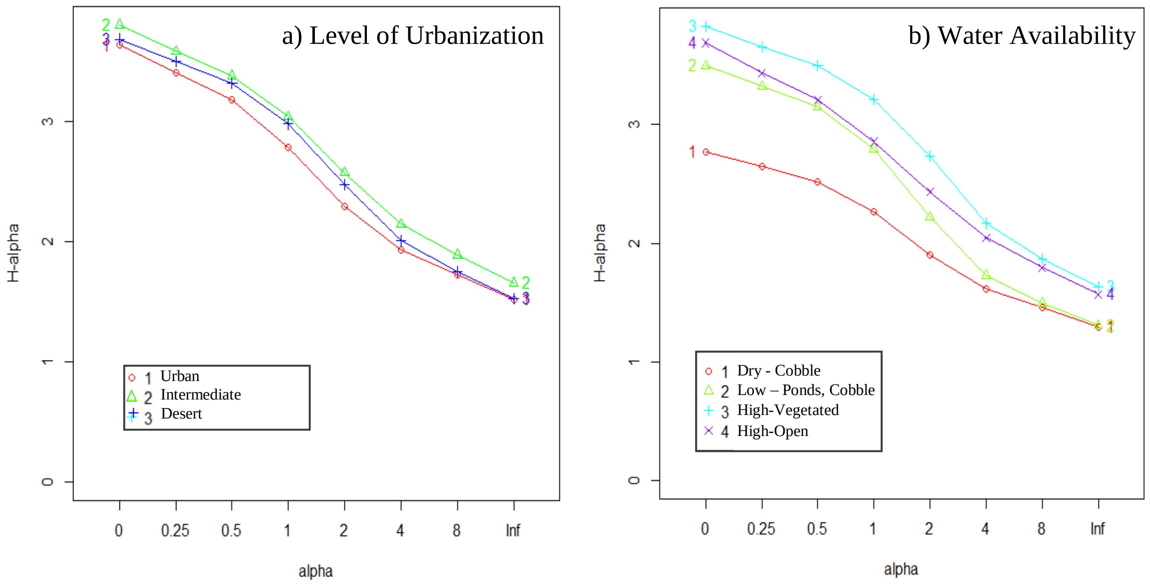


FIG 1. Renyi diversity index (H-alpha) along 36 sites placed along a gradient of water availability and urbanization between 2014 and 2016 in Phoenix, Arizona. Horizontal axis (H-alpha) represents different discrete diversity indices that move from indices that place more emphasis on richness for lower values and abundance for higher axis values. a) Renyi index of sites grouped by urbanization gradient with n=12 sites per group. Intermediate sites are the most diverse across diversity indices. Desert sites exhibit higher H-alpha values than urban sites for indices placing an emphasis on richness, but are comparable at high levels of urbanization. b) Renyi index of sites grouped along water availability gradient in groups of n=9. Sites that have intermediate levels of water availability but are vegetated exhibit higher diversity then large, open sites. Dry cobblebar sites have the lowest diversity.

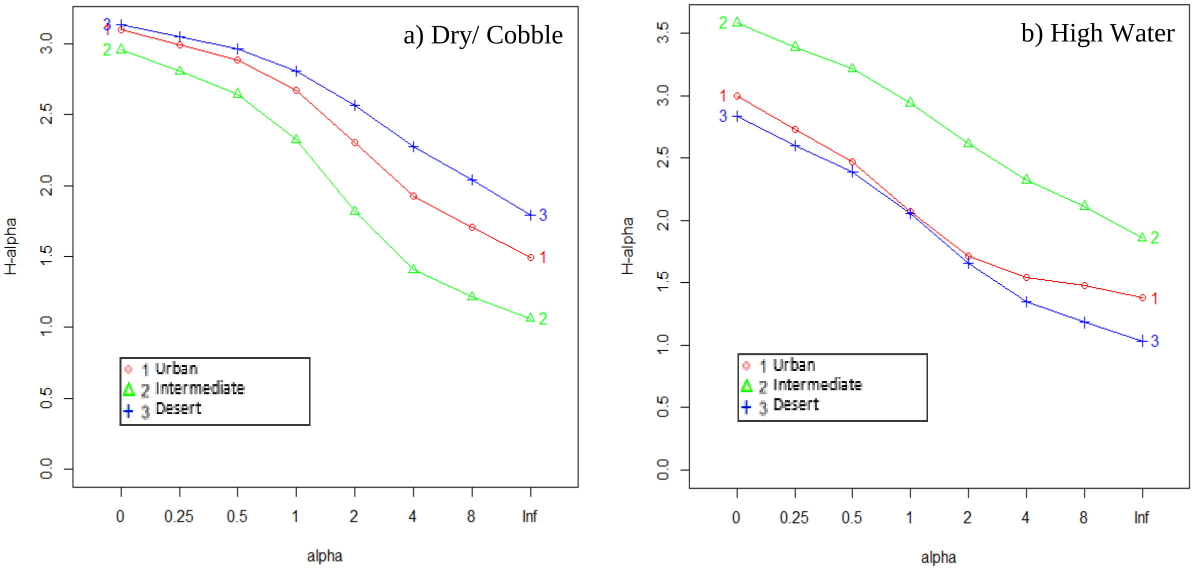


FIG 2. Renyi diversity index of urbanization gradient broken up by (a) sites within the lowest two quartiles of water availability (n=18), and (b) sites within the upper quartile of water availability. In dry sites (a) the desert has the highest levels of diversity, but this trend is reversed in sites with large amounts of water. Wetter urban sites exhibit higher H-alpha values across indices when compared to desert sites.

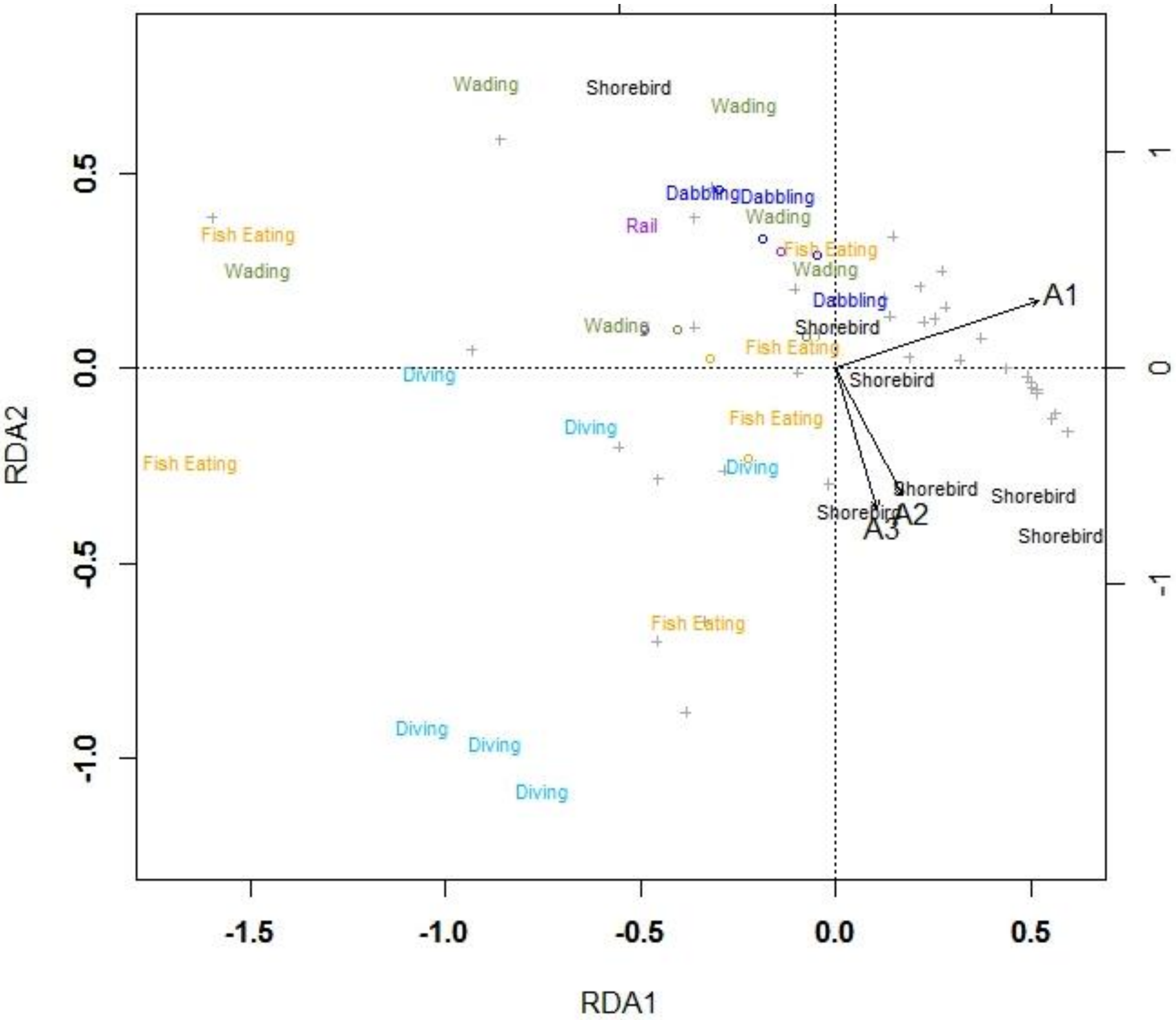


FIG 3. RDA ordination diagram of waterbird species constrained by aquatic PCA components in Phoenix, Arizona. The aquatic ordination explained 30.37% of the variation found in the waterbird community. Species in close proximity to each other indication similarity in ordination space (more likely to be found at similar sites). Vector arrow A1 describes large areas of open water, A2 is defined by shoreline complexity and emergent vegetation, and the A3 vector denotes connectivity. The length of the arrow indicates the correlation value strength between component and community composition. Component vectors closer to one another indicate higher correlation values. Dabbling ducks are represented by purple, diving ducks by light blue, fish-eating birds by dark blue, wading birds by tan, rails by green, and shorebirds by orange. RDA1 denotes a gradient of increasing water availability and RDA2 represents a gradient of emergent vegetation and connectivity.

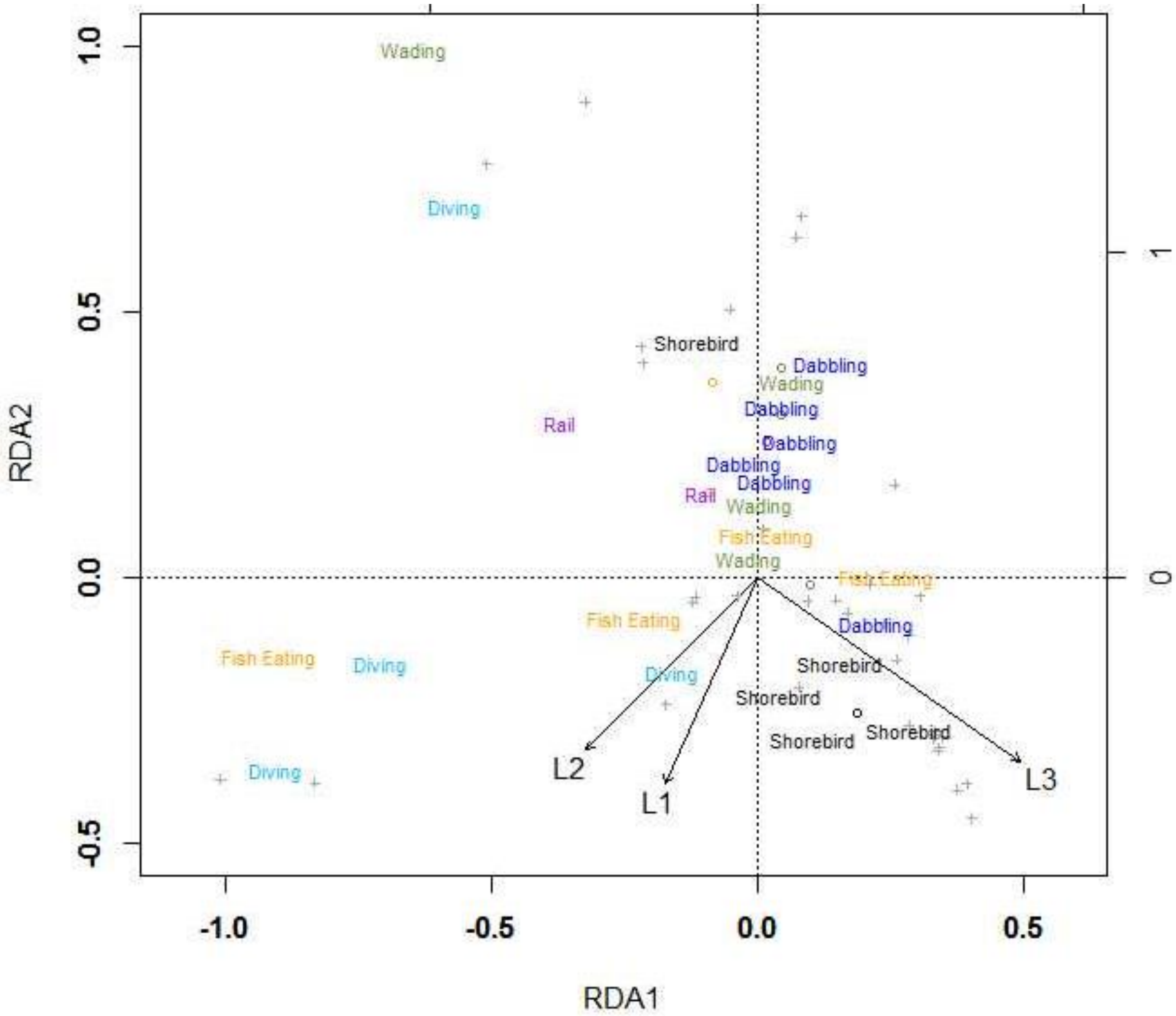


FIG 4. RDA ordination diagram of waterbird species constrained by landscape PCA components in Phoenix, Arizona. The landscape ordination explained 24.71% of the variation found in the waterbird community. Species in close proximity to each other indication similarity in ordination space (more likely to be found at similar sites). Vector arrow L1 describes urban areas, L2 is defined by agricultural land use and vegetation, and the L3 vector denotes water availability. The length of the arrow indicates the correlation value strength between component and community composition. Component vectors closer to one another indicate higher correlation values. Dabbling ducks are represented by purple, diving ducks by light blue, fish-eating birds by dark blue, wading birds by tan, rails by green, and shorebirds by orange. RDA1 displays a gradient of increasing agriculture and cultivated vegetation and RDA2 represents a gradient of land use reflective of Phoenix from desert to urbanization being represented by the middle, and agriculture at higher values.

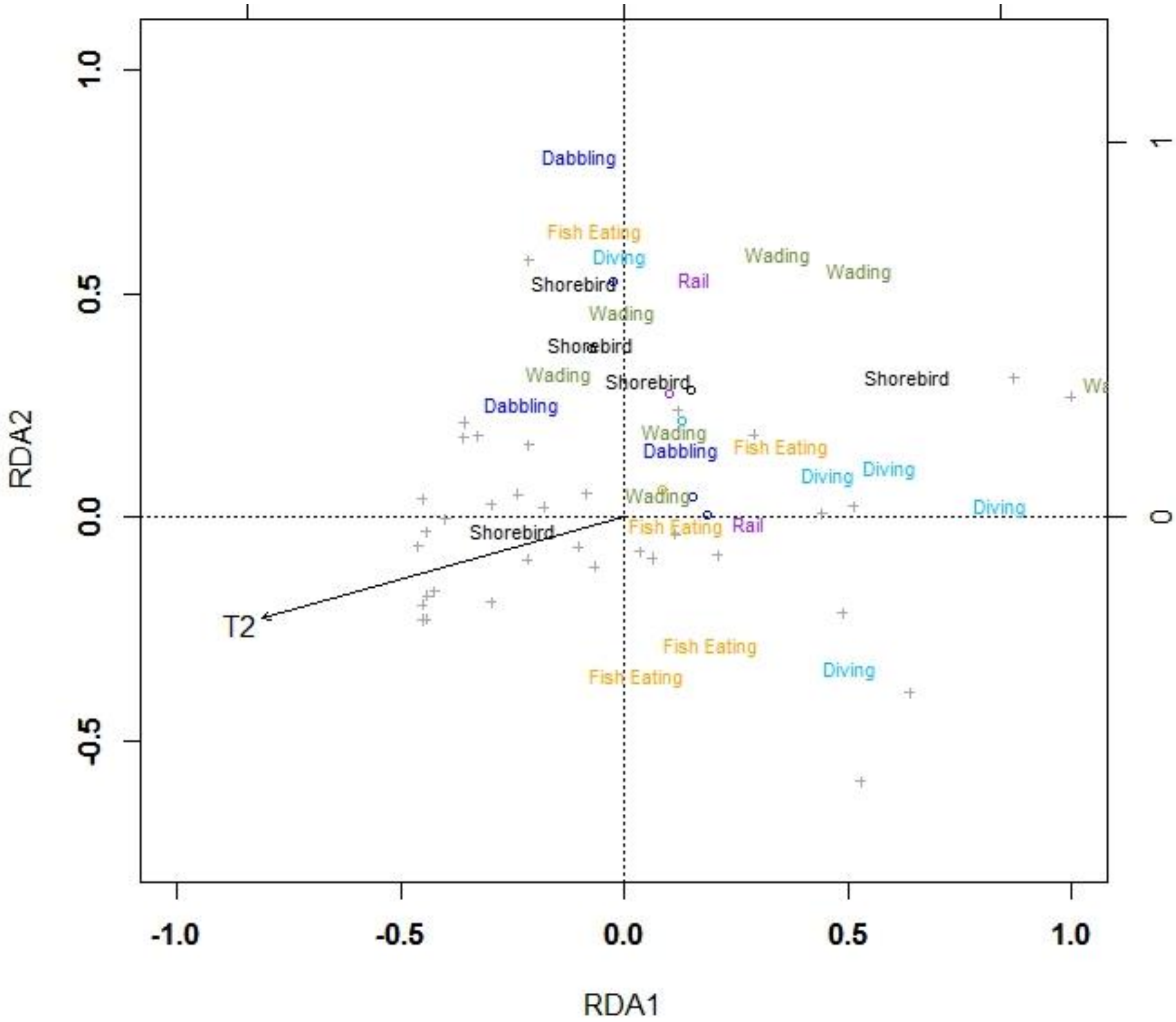


FIG 5. RDA ordination diagram displaying relationship among terrestrial PCA components and waterbird species in Phoenix, Arizona. The terrestrial ordination explained 17.93% of the variation found in the waterbird community. Species in close proximity to each other indication similarity in ordination space (more likely to be found at similar sites). Only T2 was significant and the T2 vector arrow describes vegetated ground cover. The length of the arrow indicates the correlation value strength between component and community composition. Component vectors closer to one another indicate higher correlation values. Dabbling ducks are represented by purple, diving ducks by light blue, fish-eating birds by dark blue, wading birds by tan, rails by green, and shorebirds by orange. RDA1 denotes a gradient of decreasing canopy cover and increasing percentage of bare ground.

CHAPTER 3

DISTRIBUTION MODELING FOR URBAN WILDLIFE

INTRODUCTION

Conservation efforts aimed at mitigating biodiversity loss are often focused on natural ecosystems (Lovell and Johnston 2009). However, it is imperative to recognize the environmental value of urban areas because not all land can be preserved from human activity. Landscapes should be managed in a way that benefits the maximum number of species, including our own (Waterbird Conservation for the Americas, http://www.waterbirdconservation.org/habitat.html). Urban areas can be viewed as opportunity to enhance regional biodiversity (Rosenzweig 2003).

Biotic species and communities orient themselves differently within cities, partly due to the dissimilarity in habitat from the surrounding environment (McKinney 2008). Predicting habitat suitability via species distribution modeling is a common tool used for biodiversity conservation (Rodríguez et al. 2007; Franklin 2010; Guisan et al. 2013); likewise, this technique can be applied to predict biotic responses to urbanization (e.g., Isaac et al. 2008; Isaac et al. 2013). Cities contain spatially explicit landscape mosaics, temperature regimes, and vegetation patterns (Grimm et al. 2000; Luck and Wu 2002; Buyantuyev and Wu 2010). Important biophysical variables can be mapped in the same way we map traditional landscapes used in distribution modeling, producing a predictive model relating biodiversity trends to environmental conditions for urbanized areas.

Mapping spatial relationships of biotic communities with environmental characteristics in alternative landscapes allows us to maximize the potential of wildlife habitat in cities. By considering the distribution of biodiversity within a city, planning, design, and resource management efforts that are often carried out at a local scale can be more accurately informed. Before changes made to land use, vegetation patterns, or water distribution in the urban landscape are implemented, distribution modeling can be used as a tool to predict how the conversion of these habitat patches may influence biotic diversity and distribution. For example, one of the common changes to traditional desert habitat in the arid Southwest is the redistribution of water throughout cities, offering a mesic contrast to surrounding areas.

Waterbirds, a diverse group of avifauna that provide important ecosystem functioning services (Ogden et al. 2014), have the potential to benefit from the redistribution of water within desert cities. Winter censuses in Phoenix, Arizona have determined that the high number of engineered water-bodies attract high levels of waterbird diversity and abundance, in contrast with the fact that development in less arid regions can have a negative effects on bird populations in adjacent wetlands (DeLuca et al. 2008). Other studies, such as Pearce et al. (2007), have found the negative effects of small wetlands in urban areas could be mitigated if they were in close proximity to other sources of water; creating a cluster effect and providing similar resources as one large, continuous wetland. It has been shown that birds can respond positively to urbanization or human land use if proper habitat resources are provided. For example, high bird evenness and biodiversity was preserved within green habitat patches (Ortega-Álvarez and MacGregor-Fors 2009). By identifying, understanding, and preserving areas that support waterbird biodiversity, urban conservation efforts can be better focused.

My study integrates waterbird data with biotic distribution modeling techniques to predict how waterbird communities respond to environmental variables along an urban riparian corridor. I test the hypothesis that water availability and level of urbanization will structure waterbird biodiversity distribution in Phoenix, Arizona. Specifically I hypothesize that (1) water area will be positively related to waterbird abundance and richness, and (2) level of urbanization will have a positive effect on abundance but will be relatively unimportant for structuring species richness. I included four additional environmental variables determined to be important for waterbird communities in Chapter 2, (edge ratio, perching structure, cultivated vegetation and connectivity), to discern other potential habitat characteristics that may affect the waterbird community. My approach informs the conservation of waterbird communities, but is also applicable to urban planning to better inform the outcomes of future design efforts for urban wildlife.

METHODS

Study Area

My study area focused on the Salt River, located in Phoenix, Arizona to test the effects of anthropogenic and biophysical landscape variables on waterbird community distribution patterns in an arid city (Appendix I). The Phoenix metropolitan area (33.30' N, 112.11' W) is located within the northern limits of the Sonoran desert in Arizona. According to the 2014 US Census population estimates, Phoenix has the 6th largest growth rate with a population of 4.4 million residents. Phoenix was founded as a primarily agricultural city due to the confluence of the Salt, Gila, and Agua Fria Rivers that allowed productive farming (Grimm and Redman 2004). The water from the river systems have since been diverted and redistributed throughout the city, resulting in higher levels of water availability and productivity across the desert landscape. The Salt River, which flows throughout Southern Phoenix, has been studied as part of the Central Arizona-Phoenix Long-Term Ecological Research (CAP LTER). The landscape is highly variable along the river due to land ownership, water permanence, storm drainages, restoration efforts, recreational areas, and varying management practices (Figure 6). Recent studies have shown that biotic population and community structure also vary along the river due to environmental heterogeneity (e.g. Bateman et al. 2015; Banville and Bateman 2012).

Waterbird Community Sampling

I quantified the waterbird community between the winters of 2015 and 2016 at 18 randomly stratified transects per sampling year for a total of n=36 transects (Chapter 2). Transects were placed along gradients of disturbance and water availability, spaced at intervals of at least 700m apart. Transects consisted of a 225 m by 150 m strip that was surveyed three times per year to accurately discern the species presence at each site (Conway 2011). For each survey, an observer slowly walked the transect for a minimum of twenty one minutes, recording any waterbirds seen or heard within the truncation distance of 150 m. The survey order for transects was randomized to reduce bias. To increase detection probability, surveys were conducted within four hours of the sunrise, when the wind was below 20 km per hour and precipitation no heavier than a light drizzle.

Environmental Predictors

I predicted that spatial patterns of waterbird community components would be impacted by environmental variation in the level of urbanization, water area, perching structure, connectivity, edge ratio, and cultivated vegetation (Table 7). To extract environmental variables, I used a supervised land cover classification model from February 2015 (Chapter 2). The classification model originally predicted seven land use categories: urban disturbed (residential, industrial, and commercial land use), cultivated vegetation (agriculture, irrigated grass, golf courses, and mesic yards), riparian vegetation, impervious surface, water, river gravel/ bare ground, and undisturbed (desert, desert shrub, urban desert remnant parks). From this analysis, I extracted individual rasters for urban, water, and cultivated vegetation.

For level of urbanization and cultivated vegetation I constructed the environmental rasters by summarizing the percent of the land cover variable within 1.5 km of each cell. To create the water area raster, I assigned each raster cell within a body of water a value equal to its total area; if the cell did not fall within a body of water it was assigned a value of zero. The edge ratio was calculated by dividing the perimeter of each water polygon by its area and converting to raster format, as with the water area raster, cells that did not fall within water classification were assigned a value of zero. The edge ratio describes the shape of the wetland and can be defined as: the amount of shoreline per area of water. Higher edge ratio values describe complex shorelines, while lower values describe large round bodies of water.

Perching structure can increase foraging success for a number of waterbird species and is typically found in recreational-use areas. I used a spatial overlay of disturbed land use, cultivated vegetation, and water area to produce an index raster predicting the probability of available perching structures. If no water was present, the probability for perching structure was assigned a value of zero. The result was a raster predicting that large bodies of water located in urbanized areas contain a higher probability of containing perching structures.

To determine the connectivity of the Salt River, I calculated the Euclidean Distance between each water polygon, creating a distance based raster. Individual environmental rasters were spatially joined with bird survey data collected in Chapter 2 at the center of each transect using the Spatial Analyst Extraction tool. This produced a matrix of sites with the biotic community data and environmental variables for the center of each transect.

Community Models

The methodology for species distribution modeling can be modified to predict how entire communities may react to physical changes in the environment (Ferrier and Guisan 2006). By broadening focus to community level outcomes, it can be determined what environmental factors will increase the diversity of the region as a whole, not just the success of a few select species. I employed the 'Assemble First- Predict Later' strategy proposed by Ferrier & Guisan (2006) to determine how the spatial variation of the six environmental variables affect waterbird biodiversity distribution (Table 7).

I first aggregated the waterbird species into foraging guilds that exploit the same group of environmental resources (Elphick and Dunning 2001; Melles et al. 2003). The waterbird species observed in my study were clustered into six guilds: dabblers, divers, fish-eating birds, shorebirds, rails, and waders. The relative abundance for each of the foraging guilds, herby referred to as guild abundance, was calculated by averaging the sum of abundance for all species per guild and standardized per area of water.

Additionally, I calculated waterbird species richness (total species detected on any of the three surveys per transect).

I generated predictions of guild abundance and richness in each 30 m grid cell based on measured bird data and environmental variables using General Additive Models, GAMs (Hastie and Tibshirani 1990). GAMs are appropriate to model community level data due to their estimation of response curves using local smoothing functions. Therefore, they have more flexibility than Generalized Linear Models to explore complex relationships that may appear with multi-species data. I developed ten a priori models (Appendix III) for each community component to describe guild abundance and diversity and then applied each set of models against bird survey data. The a priori models included at six models with level of urbanization and water availability to compare the importance of these two central research variables across various community responses. I examined the response curve (guild abundance and richness) with the model including level of urbanization and water area to determine the response curve shape. Additional variables selected for the model were driven by environmental conditions predicted to be important for each waterbird community response (Chapter 2) and are listed in Table 7. Cultivated vegetation, edge ratio, perching structure, and connectivity were all determined to be important for guild abundance or richness in Chapter 2 analysis and were selected when building a priori models. The top performing model was selected for each community measurement based on the lowest relative Generalized Cross Validation (GCV) score and highest deviance explained (Craven and Wahba 1979). Small GCV scores indicate lower predictive error in the model and deviance explained reports the proportion of null deviance of the response variable that the model is able to explain. If two models performed similarly, I performed an ANOVA and AIC analysis to see if the more complex model performed significantly better than a more parsimonious option. The final ‘best-fit’ GAMs connected community level bird data to environmental predictors with an identity link predictive function (Gaussian) for guild abundance and a log link predictive function (Poisson) for richness using smoothing splines to highlight the relative magnitude of affect for the selected variables.

I visualized the predictions from these models for each community component on the raster grids of the Phoenix metropolitan area. The six predictive guild maps (see Appendix IV) were assembled to create an abundance hotspot map predicting overall abundance for Phoenix, Arizona. The richness map was the direct output of the richness model prediction. The values (abundance and richness) from the two predictive maps were extracted for each site location to compare observed versus predicted response using a Spearman's correlation coefficient and the Mean Absolute Percent Error (MAPE).

RESULTS

The Effects of Water and Urbanization

My hypothesis that water availability and land use would be drivers of the waterbird community distributions in Phoenix was partly supported. Guild abundance and biodiversity models supported the importance of water area but not level of urbanization (Table 8). My hypothesis that urbanization would directly increase abundance was not supported by the GAM abundance models. Level of urbanization was only included in one of the six abundance models, (rail abundance), whereas, my hypothesis that urbanization would not impact richness was supported and was not included in the richness model. Water area had a large impact on guild abundance for all guilds but was excluded from the species richness model (Table 8). The URBAN + AREA additive models were not included in any of the top performing models for community response variables, but illustrated some general trends between waterbird abundance and the two gradients (Figure 7). Guild abundance peaked at median values of urbanization for five of the six guilds, while area of water had a variety of relationships depending on species and level of urbanization. Dabbling ducks exhibited highest levels of abundance at intermediate levels of urbanization and showed an asymptotic relationship with water area (Figure 7). Dabbling ducks were positively related to water area at low levels of urbanization, and were more strongly tied to intermediate-sized water bodies as urbanization increases (Figure 7). Rails, fish-eating, and wading birds were affected similarly by the two variables (Figure 7). Area of water exhibited a non-linear relationship in the included models and tended to level out at higher values (Figure 7). Only the rail (predominantly composed of American Coots) abundance model included both terms in the best-fit model. Edge ratio and cultivated vegetation were also included in a majority of the abundance models (Table 8). Connectivity was included in the a priori models for shorebirds and species richness, and was selected for in best-fit richness model.

Community Response Curves

Guild abundance was best predicted by a combination of environmental variables in addition to water area and urbanization. Area of cultivated vegetation was positively associated with dabbler abundance ($P<0.001$, Figure 8); whereas, shoreline complexity ($P<0.048$) and area of water ($P<0.658$, Figure 8) had a quadratic relationship with dabbling ducks. Both diving ducks and fish-eating bird abundance was driven positively by area of water ($P<0.0004$; $P<0.20$, Figure 8), which was included as a non- linear term and displayed an asymptotic trend at higher values (Figure 8). Abundance of the two guilds were also negatively related to shoreline complexity ($P<0.0001$; $P<0.11$, Figure 8), respectively; fish-eating birds were positively related to perching structure ($P<0.001$), used for resource acquisition; whereas diving ducks were negatively related to perching structure ($P<0.001$, Figure 8).

Rail species (primarily American Coots) were the only guild that included urbanized areas ($P<0.232$) in their best fit model. Rails were also positively associated with a tensor-smoothed term of cultivated vegetation and water area ($P<0.001$, Figure 9). Shorebirds were the sole guild negatively associated with area ($P<0.0001$, Figure 9). Connectivity was hypothesized to be important and was included in shorebirds' set of a priori models based on Chapter 2 analysis; however, it was not included in the best-performing model. Shorebirds had a strong positive relationship with shoreline complexity, preferring long- narrow habitats to forage. Wading birds were the sole guild associated with connectivity, in addition to perching structure used to roost as a tensor-smooth, and cultivated vegetation ($P<0.0001$; $P<0.025$ Figure 9).

The species richness model indicated that the amount of water present had a positive association with waterbird biodiversity ($P<0.071$, Figure 10) that peaked at intermediate levels of water area (similar to the Renyi Index results in Chapter 2). Connectivity was not found to be important in the abundance models, but was significant in the top model for species richness ($P<0.0115$, Figure 10). Richness was greatest in sites at high and intermediate levels of connectivity. Richness displayed a threshold response and declined rapidly at sites with low connectivity. Species richness was positively associated with cultivated vegetation (P<0.0001, Figure 10).

Biodiversity Hotspots

The abundance model predicted abundance to range from 0-360 individuals per survey throughout the entire study area, the actual maximum number of individuals observed at a given site was 327 (Figure 11). The predicted maximum also occurred in a similar area of the observed maximum. Similarly, my model predicted a range of 2 to 30 species per site, observed maximum species richness was 29; again my prediction aligned spatially with observed richness (Figure 11). Overall, my predictive models predicted comparable results to actual observed patterns in Phoenix (Figure 12).

Urban areas provided the highest percentage of habitat that supported high waterbird abundance and intermediate levels of urbanization had a significantly higher abundance than desert (Table 9). Proportionally, intermediate areas supported high levels of waterbird richness. Approximately 53% of intermediate habitat available was suitable for high richness levels, comparable to urbanized areas with 41% of available habitat, and much higher than 7% of the desert. The largest area of both biodiversity and abundance occurred in the Southwest edge of Phoenix, an area of intermediate levels of urbanization and high agricultural usage (Table 9). Tres Rios, a water treatment plant is also located within this area (Figure 11). Other key hotspots for abundance and biodiversity included: Tempe Town Lake, Granite Reef Dam, and Saguaro Lake (Figure 11). Richness was comparable across the gradient of urbanization, and was the lowest in drier habitats. Although larger lakes were important in predicting higher levels of guild abundance separately, the accumulative map had a lower overall effect. For example, Saguaro Lake was predicted to house comparatively high levels of abundance, but was not one of the highest areas for richness. Granite Reef Dam (small with a larger edge ratio and emergent vegetation) had lower predicted levels of abundance, but higher levels of richness (Figure 11, lower quadrant).

DISCUSSION

Recent studies have indicated that waterbirds either respond positively to anthropogenic land use (Young 1998; Masero 2002), or land use may be relatively unimportant when compared to water body physiognomy and local habitat characteristics (Rosa et al. 2005). This has also been documented in terrestrial species; Isaac et al. (2008) demonstrated urbanized areas have the potential to support rare avian apex predators. Overall, my study provided support the assertion that urbanization does not exclude waterbird when it provides water resources.

As a functional group, waterbirds are tied to aquatic resources for crucial activities needed for survival, such as foraging and roosting. Cities located in dry climates often provide higher levels of water and productivity when contrasted to the outlying desert (Larson et al. 2005). The success of waterbirds in highly urbanized landscapes may be partially attributed to this factor, especially in arid environments. I found the gradient of water availability was a much larger driver of the waterbird abundance and richness than level of urbanization. Habitat connectivity was also an important component for describing waterbird richness. Connectivity has been shown to be a potential barrier for dispersal in fragmented urban areas (Desrochers and Hannon 1997); however, barriers to dispersal are unlikely for waterbirds within a city because they move at such large spatial scales. For example, satellite telemetry determined Mallards in Arkansas migrated, on average, 172 km per day with a total migration length of over 1600 km (Krementz et al. 2011). Instead of providing dispersal conduits, increased connectivity is likely important because smaller clusters of discrete wetlands accumulate to a larger area (Pearce 2007; Gledhill and James 2008). Increased heterogeneity of habitat characteristics supports a more diverse assemblage of species within the given cluster, an additional benefit of Phoenix's distribution of water.

Additional habitat characteristics had an unexpected impact on structuring the community in Phoenix. In my models, edge ratio (related to the shape and complexity of the shoreline) was a major factor, as well as cultivated vegetation. These variables indicate a connection to habitat selection based on foraging mechanisms. Guilds such as wading birds, shorebirds, and rails use the shoreline to forage for respective resources and benefit from an increased area to support food acquisition. Likewise, cultivated vegetation can also be beneficial for the foraging strategies of multiple species. The association of waterbirds with agricultural land use for foraging has been documented in literature (Ohmart et al. 1985) and I also found that the presence of agricultural land use (cultivated vegetation) resulted in higher abundance and richness for adjacent sites. In its initial development, Phoenix was primarily an agricultural city (Jenerette and Wu 2001). As Phoenix expanded, the urban center was transformed, while the agricultural areas were constrained to the outskirts of the city (see Appendix I). Therefore, intermediate areas of urbanization in Phoenix are also more likely to be associated with increased agricultural land use. In general, intermediate development has been associated with peaks in wildlife abundance and diversity (Blair 1996, 1999, 2004). My study supports this trend, but partly attributed it to the structure of the surrounding matrix, which was primarily agricultural land use.

Level of urbanization was largely unimportant in the best-fit models used for predicting and mapping waterbird abundance or richness in Phoenix. However, when looking at the gradient effects of water and urbanization individually (Figure 7), abundance tends to peak at intermediate levels of urbanization. Likewise, when looking at the predicted abundance for the levels of urbanization, intermediate areas are predicted to support higher average abundances than either urban or desert. This suggests that although level of urbanization does not have a direct effect on waterbird abundance, other important habitat characteristics (such as proximity to agriculture) that is related to urban land use patterns, can have a positive or negative effect on abundance in a particular area. This is supported by the GLM models in Chapter 2; when urbanization is grouped in relationship to ancillary variables it becomes important as part the abundance models, but is unimportant as an isolated variable.

The relationship of environmental variables seem to be one of the determining factors in whether or not urbanization will negatively impact a specific taxon. In Tucson, Arizona, Mills et al. (1989) found vegetation factors were more important than housing density in explaining variation in terrestrial breeding bird communities. However, as housing density and paving increased in Tucson beyond moderate levels, both connectivity and native vegetation also decreased, resulting in an overall loss of bird richness and abundance (Germaine and Wakeling 2000). Melles et al. (2003) found that habitat and landscape-level habitat features were directly related to the decline of species richness in relation to increasing urbanization. This supports my conclusion that higher waterbird abundance and biodiversity in metro-Phoenix is primarily driven by the overall increase in area and heterogeneity of available aquatic habitat provided by urbanization.

Phoenix has over 1,400 artificial lakes and wetlands (Larson and Grimm 2012). As a common outcome of urbanization, many of these areas have been developed for public amenities. For example, Tempe Town Lake (Figure 6) was built for flooding mitigation, with additional benefits such as recreational activities and economic stimulation. However, it was also found to be one of the areas for supporting abundant fish-eating birds. This can be viewed as positive for waterbird conservation efforts and as a negative for managers that stock the lake for recreational fishing; highlighting one of the potential conflicts of urban wildlife management.

Tempe Town Lake is also linked to conservation and sustainability initiatives, such as habitat restoration of the riverbed surrounding the lake. In fact, many of the riparian habitat restoration initiatives in Phoenix have had positive outcomes. Actively restored reaches of the Salt River have greater species richness of birds and herpetofauna than unmanaged sites due to direct planting and focused irrigation (Bateman et al. 2015). Another example of this would be the Tres Rios Wetlands in Phoenix, a constructed waste-water treatment plant that provides 480 acres of emergent wetlands. Although providing waterbird biodiversity is not the primary purpose of the area, managers have constructed islands with perching structure and stock the water cells with fish, resulting in one of the largest concentrations of waterbird abundance and richness in Phoenix. During the 2012 Christmas Bird Count, over 250 active Neotropic Cormorant nests were observed in the willows and cottonwoods planted on the islands (http://www.azfo.org/namc/IndexphoenixUrban.html). Likewise, smaller areas such as the Rio Salado Habitat Restoration Area and Base and Meridian Wildlife Area, provide hiking trails and recreational opportunities in addition to bird habitat. Although the Salt River may have little to no waterbird habitat available in highly disturbed, dry reaches of the river bed, these types of restoration activities demonstrate how habitat can be optimized at a landscape scale for the dual benefit of both humans and wildlife.

In conclusion, my study demonstrates how advances to distribution modeling methods in conjunction with the availability of spatial data sources allow for the exploration and prediction of anthropogenic effects on biodiversity (Guisan and Thuiller 2005). I used this methodology to predict current distributions of biodiversity throughout an urban area, but it could also be used similarly to models predicting species' response to climate change or large scale land use (Hansen et al. 2001; Jetz et al. 2007; Jongsomjit et al. 2013), only applied to future conservation efforts (Franklin 2010; Franklin 2013). Moving forward, further research can be the extension of modeling current distribution trends into the futures of cities to help us understand the potential impacts to change. Managing key habitats within urban areas confers the protection of current populations and offers the opportunity to conserve, design, and improve additional resources that optimize potential habitat.

TABLE 7. Definition and collection methods for six biophysical variables used to model macro-ecological components of the waterbird community in Phoenix, Arizona between 2015 and 2016. Variables were derived from a supervised land cover classification performed on 30 m resolution Landsat Image taken in the winter of 2015.

Variable	Definition
Urbanization (URBAN)	Proportion urban or impervious surface land cover classes of 30 m-pixels in a 1.5 km area urban land use
Water area (AREA)	Surface area of each discrete water body
Perching structure (PERCH)	Index predicting relative value of artificial perching structure by summing AREA, URBAN, and CULTVEG rasters for each discrete water body
Connectivity (CONNECT)	Euclidean distance in km to nearest water polygon
Edge Ratio (EDGE)	Shoreline complexity (Perimeter km/ Area hectares) for each discrete water body
Cultivated Vegetation (CULTVEG)	Proportion of agriculture and grass land cover classes of 30 m-pixels in a 1.5 km area urban land use

TABLE 8. Parsimonious best-fit model selected for macro-ecological response of waterbirds to environmental predictors in Phoenix, Arizona. Models were selected from ten a priori models developed for each community component that had the lowest GCV and explained the largest amount of deviance. If two or models preformed similarly, an F-test and AIC comparison was completed to ensure that adding an additional term made the model significantly better at explaining response variable. s() indicates a smoothed term and te() indicates a tensor smooth.

Response	**Model**	**R^2**	**GCV***	**Dev. Exp.****
Dabbler abundance	s(EDGE) + s(CULTVEG) + s(AREA)	0.70	<0.01	81.8
Diver abundance	AREA + s(EDGE)+ s(PERCH)	0.79	<0.001	88.7
Fish abundance	PERCH + s(AREA) + s(EDGE)	0.74	<0.001	83.9
Rail abundance	s(URBAN) + te(AREA, CULTVEG)	0.72	<0.03	87.4
Shorebird abundance	te(AREA, EDGE)	0.76	<0.001	89.1
Wader abundance	te(PERCH,CONNECT) + s(CULTVEG)	0.63	<0.004	77.4
Richness	s(AREA) + s(CULTVEG) + s(CONNECT)	0.77	0.26***	82.8

* mean square prediction error. GCV = (n * scaled est.) / (n - edf - terms)^2

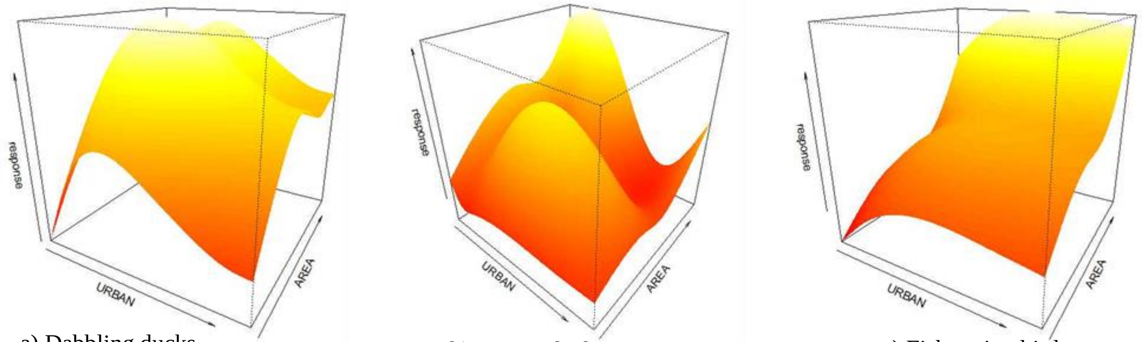
** Deviance Explained (%)

*** Poisson Distribution: UBRE error measure

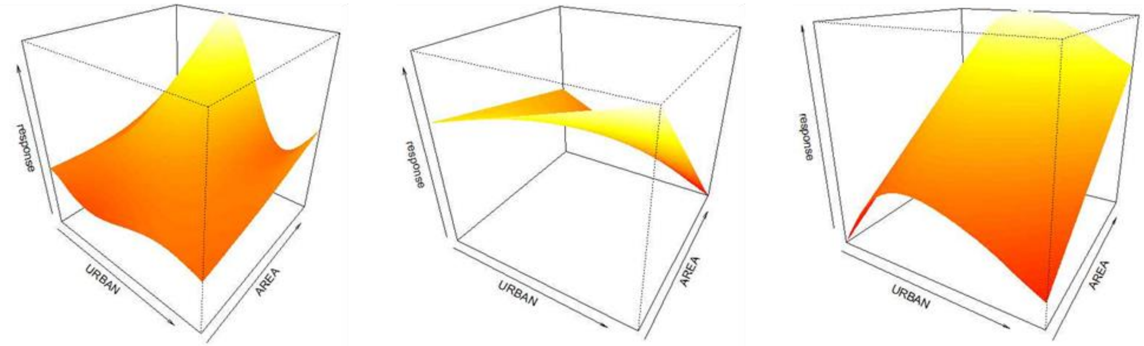
TABLE 9. Predicted proportion of highly suitable habitat (above one standard deviation of the mean) along urbanization and water gradients in Phoenix, Arizona. Estimates were derived from the water area polygons as the area of water providing highly suitable habitat per the total amount of raster cells within each of the gradient levels.

Gradient	Description	Abundance	Richness
Water Availability			
4	High	0.94	0.49
3	Intermediate	0.05	0.33
2	Low	0.01	0.13
1	Dry	0.00	0.04
Level of Urbanization			
1	Desert	0.22	0.07
2	Intermediate	0.25	0.53
3	Urban	0.52	0.41

FIG 6. Collage depicting heterogeneity of sites available to waterbirds throughout the Salt River located in Phoenix, Arizona. The river varies in terms of water availability and physical environment caused by differing land use, ownership, restoration, and design strategies as you move across the city. a.) Tonto National Forest- desert site, (b.) Base and Meridian Wildlife Area in Southwest Phoenix- restored wildlife area, (c.) Base and Meridian Wildlife Area, (d.) Tempe Town Lake marsh- highly urban, (e.) 35th avenue drain, and (f.) Tres Rios Wetlands- water treatment site.



a) Dabbling ducks b) Diving ducks c) Fish-eating birds



d) Rails e) Shorebirds f) Wading birds

FIG 7. Response curves for waterbird guild abundance along a gradient of urbanization and water area, for (a) dabbling ducks, (b) diving ducks, (c) fish-eating birds, (d) rails, (e) shorebird, and (d) wading birds in Phoenix, Arizona. Lighter shades indicate higher predicted response to environmental variable and darker shades indicate lower predicted abundance. Guilds abundance in general, peaked at intermediate levels of urbanization and had complex but positive association with water area.

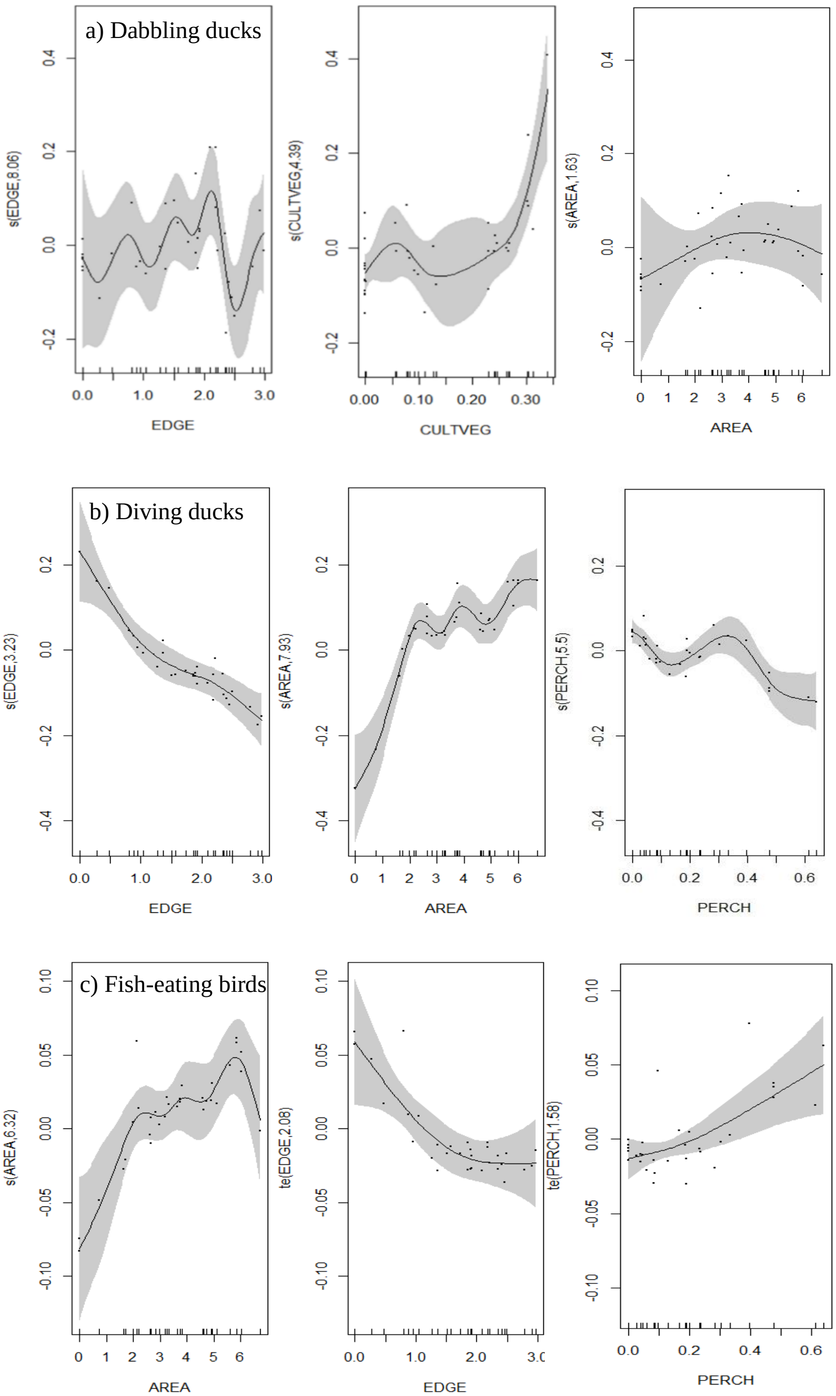


FIG 8. Abundance response curves for (a) dabbling ducks, (b) diving ducks, (c) fish-eating birds with biophysical variables found in each respective the best-fit model selected from ten a priori models for Phoenix, Arizona. Abundance is defined as waterbird abundance per standardized area of water. X-axis is labelled as covariate values and the y-axis is labelled as (covariate name, edf), where edf is the estimated degrees of freedom of the smooth.

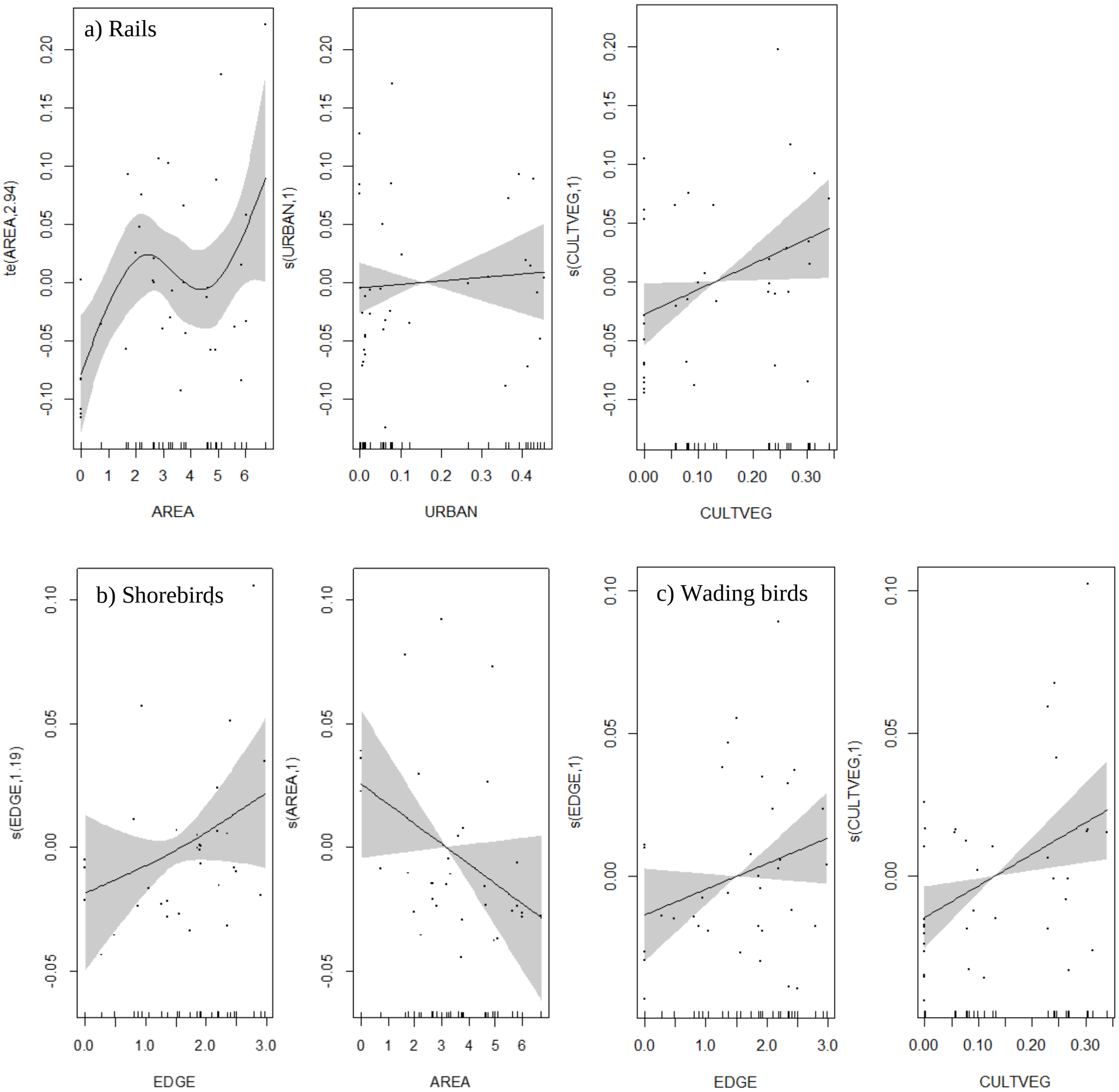


FIG 9. Abundance response curves continued for (a) rails, (b) shorebirds, and (c) wading birds with biophysical variables found in each respective the best-fit model selected from ten a priori models for Phoenix, Arizona. Abundance is defined as waterbird abundance per standardized area of water. X-axis is labelled as covariate values and the y-axis is labelled as (covariate name, edf), where edf is the estimated degrees of freedom of the smooth.

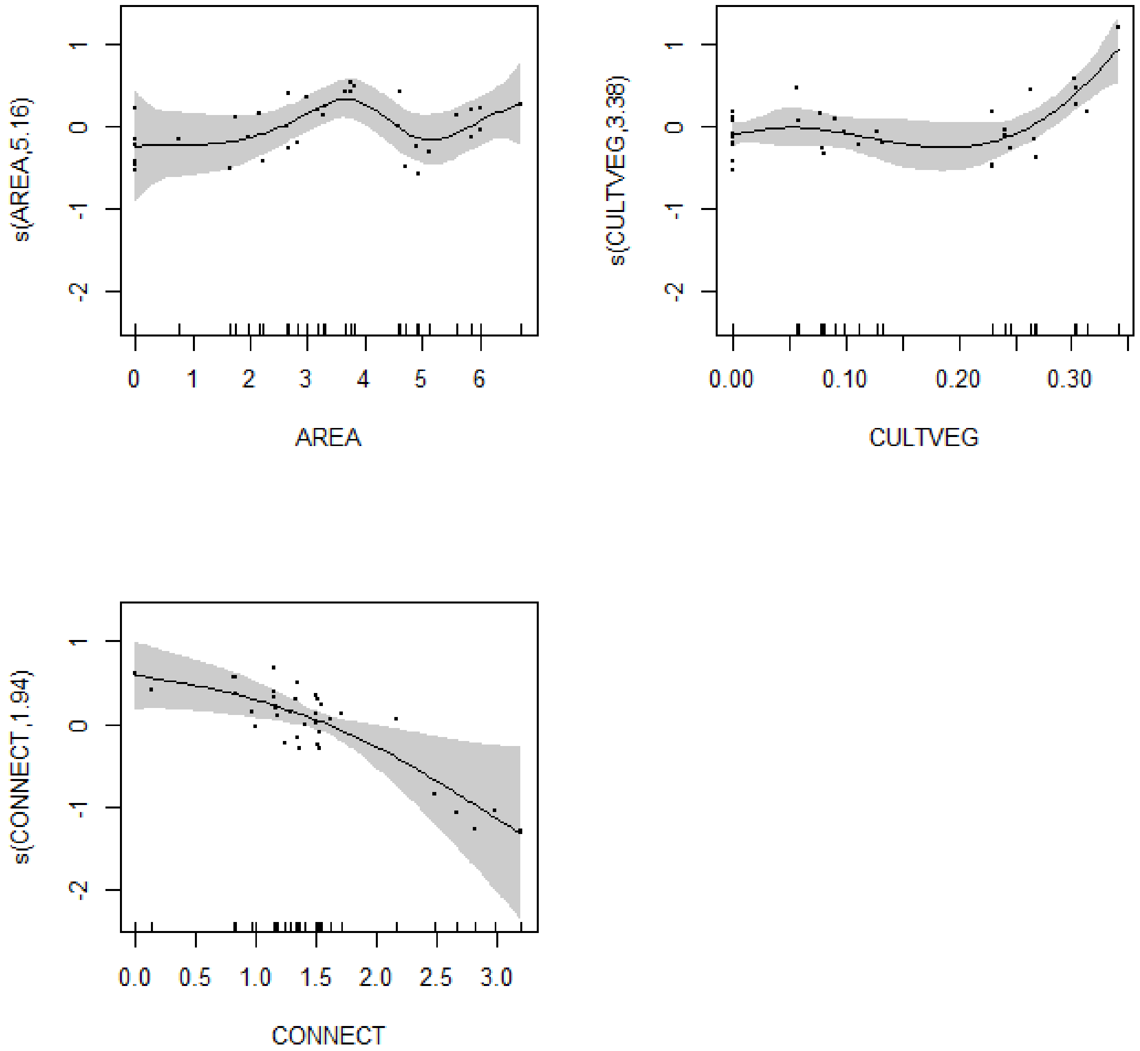


FIG 10. Response curves for waterbird species richness with the environmental predictors in Phoenix, Arizona along a gradient of urbanization and water availability. X-axis is labelled as the range of covariate values included in the model and the y-axis is labelled as (covariate name, estimated degrees of freedom of the smooth).

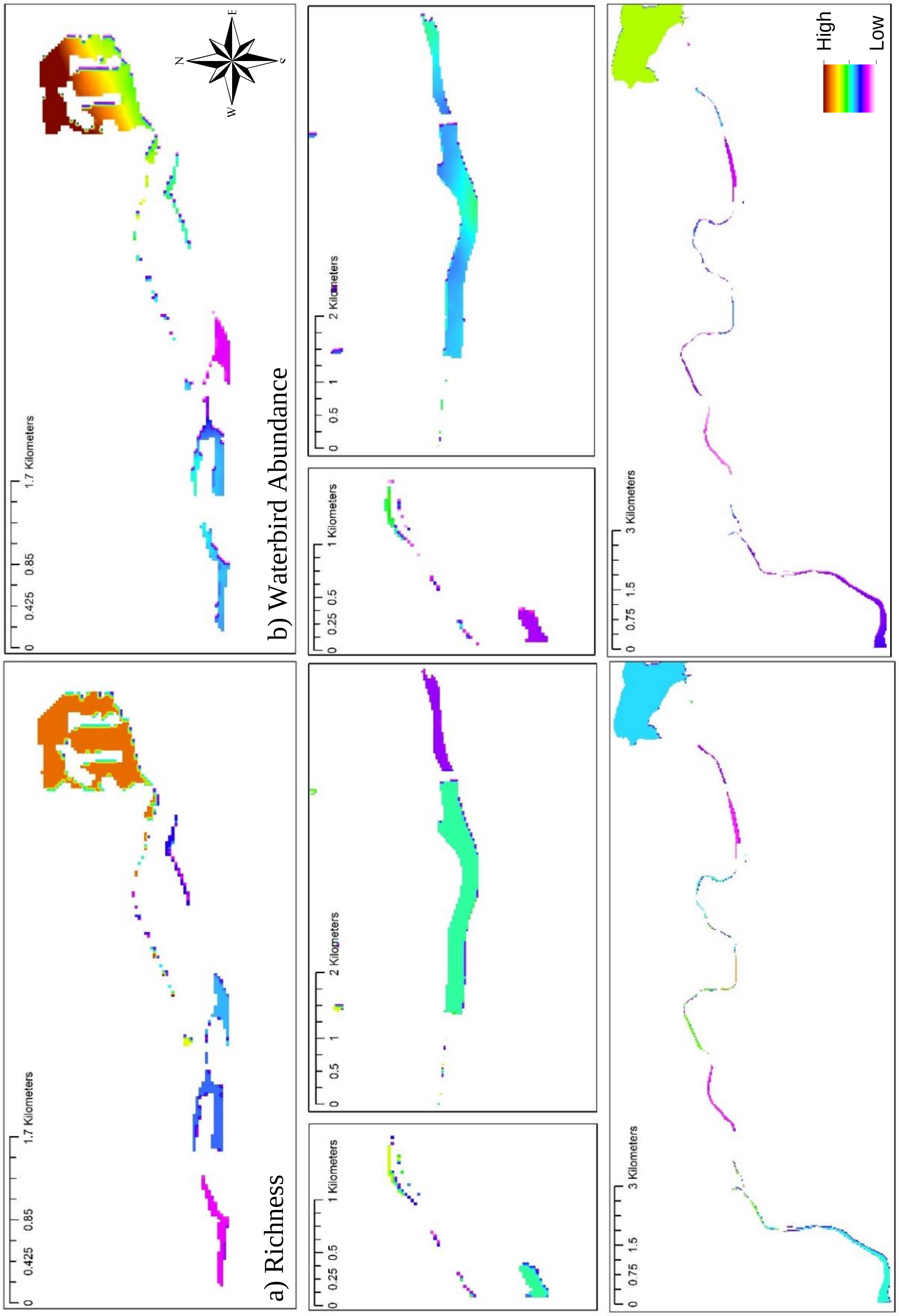


FIG 11. Predictive maps of hotspots for (a) species richness and (b) waterbird abundance per area water across the entirety of the study area by overlaying predictive distribution maps. Species richness values were predicted to range from 2 to 30 and average abundance was predicted to range from 2 to 360.

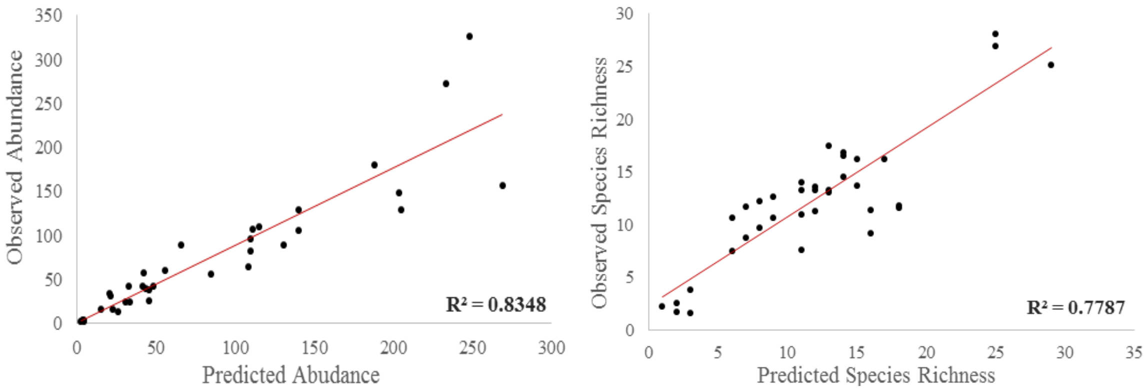


FIG 12. Accuracy assessment of observed versus predicted values for overall waterbird abundance and species richness at n=36 sites along the Salt River in Phoenix, Arizona. The listed R^2 value was significant at P<0.0001 for both models based on a Pearson product-moment correlation. The Mean Absolute Percent Error (MAPE) of the abundance model was 0.27 and the richness model MAPE was 0.26.

CHAPTER 4

CONCLUSION

My research study affirmed that urbanization does not always have negative consequences on waterbird populations. I linked waterbird community parameters to habitat and landscape variables to identify a number of important environmental characteristics for waterbird community success. I found that water physiognomy was the largest driver in shaping waterbird community components in an arid city. Water extent was important, but this relationship was also asymptotic; once a certain threshold was reached, increasing water area did not necessarily add to a comparable increase in abundance or richness. Interconnectedness of wetlands were important for diversity measures, but not for individual guild abundance. Combining these conclusions with the importance of shoreline complexity, water bodies that support the highest levels of biodiversity will be intermediately sized with ample shoreline. Alternatively, smaller bodies of water close together to increase the shoreline to water ratio while maintaining an overall level of water will also help support waterbird communities. Land use helped shape the suite of species at each site, but was not relatively important for overall abundance or diversity; supporting my hypothesis that urban lakes can support healthy waterbird communities. This effect can be enhanced by managing habitat characteristics to maximize the usefulness of a single area. The heterogeneity of habitat in Phoenix optimized the area available for the specific foraging needs of the various waterbird guilds. For example, Tempe Town Lake provides a large open body of water for fish-eating birds, diving, and dabbling ducks; while an adjacent drain less than 500m away offers a narrow, vegetated strip to support wading birds and rails. Both of these areas also provide municipal services such as recreation and flood mitigation.

Spatial nestedness of a riparian area and the specific landscape arrangement of Phoenix may have caused confounding effects. For example, intermediate areas were typically closer to agricultural land use. Therefore, it is difficult to separate certain landscape characteristics from one another. I dealt with this in Chapter 2 by combining variables that describe similar areas with a Principal Component Analysis; however, urban waterbird studies would benefit from focusing on a mechanistic study that breaks down the effects of a few specific variables that have now been identified as important across multiple studies. Temporally, my study was conducted in two, wet, el-Niño years, and results collected in a drier winter may change some of the interactions between waterbirds and their environment. However, I assert drier years would make my findings on the importance of water and productivity inside cities more pronounced, not less. Additionally, the increase of productivity and water within arid cities may also cause conflicting results if compared to a similar study done in a wetter climate. A long-term, multi-city approach would help determine what trends hold true globally, while maximizing localized conservation knowledge.

Biodiversity can benefit ecosystem functioning (Naeem 2002) and waterbirds in particular can greatly contribute to ecosystem health (Green and Elmberg 2014). Urban riparian areas are often a direct interface between humans and nature, and can catalyze socioeconomic and ecological revitalization of cities (Groffman et al. 2003). A combination of aquatic features can provide a number of ecosystems services, including increased biodiversity, and a better understanding of the system will allow for managers to direct decisions for desired outcomes (Hansson et al. 2005).

This work addresses the relationship between aquatically dependent species in an arid city. I show that aquatic features not originally intended for wildlife conservation purposes can still sustain a large, diverse community. As the importance of the trade-offs for water conservation efforts increase, we must be aware of how planning and management decisions affect urban biodiversity. My study shows that it is possible to maximize the services that a particular blue space offers and should be taken into consideration as areas with water are either built or removed from the urban landscape.

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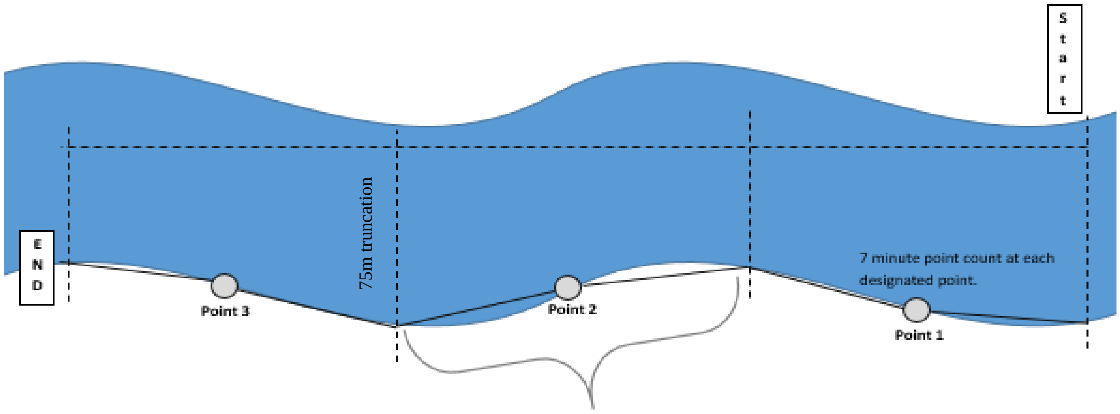
APPENDIX I

STUDY AREA MAP OF TRANSECT DISTRIBUTION ALONG THE SALT RIVER IN PHOENIX, ARIZONA

FIG A1-1. Location of the study area in Phoenix, Arizona. 36 transects were randomly stratified along a gradient of water availability and urbanization (desert, urban, and intermediate). Landscape depicted shows an overlay of urban (brown to tan), cultivated vegetation (light green), canopy cover (olive green), and water area (blue to grey) classification rasters that were used to derive landscape environmental variables and for spatial analyses.



7 minute point count at each designated point.

Slowly walk to next point, counting any birds seen or heard in 75m segment. Estimate distance to bird.

FIG A1-2. Sampling design of 36 transects relative to river. I randomly stratified transects along a gradient of water availability and urbanization in the Salt River, Phoenix, Arizona. Transects were 225 meters in length and placed at least 700 m apart. An observer slowly walked each transect for a minimum of 21 minutes and recorded any birds seen or heard within a truncation distance of 75 m from observer for a total transect area of 225 x 150 m.

APPENDIX II

WATERBIRD SPECIES OBSERVED IN PHOENIX, ARIZONA BETWEEN 2015 and 2016

TABLE A2-1. Species and guild list of waterbird species observed along the Salt River in Phoenix, Arizona between the winters of December 2014- February 2016. Waterbird species are organized by foraging guild for analysis. Dabbling ducks (Dabbler) are stocky bodied species that forage by dipping head first into the water to feed on plants and aquatic vegetation, diving ducks (Diver) are foragers that dive beneath the surface to find food, fish-eating birds (Fish-eating) chase prey beneath the surface with powerful propulsion, rails (Rail) are marsh species that utilize emergent vegetation for foraging structure and protection, shorebirds (Shorebird) are species that largely forage in shallow water on vegetation and invertebrates, and wading bird (Wader) are species that wade in search of prey.

Common Name	**Guild**	**Scientific Name**
Northern Shoveler	Dabbler	*Anas clypeata*
Green-winged Teal	Dabbler	*Anas crecca*
Mallard	Dabbler	*Anas platyrhynchos*
Gadwall	Dabbler	*Anas strepera*
Cinnamon Teal	Dabbler	*Anas cyanoptera*
Blue-winged Teal	Dabbler	*Anas discors*
Canada Goose	Dabbler	*Branta canadensis*
Northern Pintail	Dabbler	*Anas acuta*
Fulvous Whistling-Duck	Dabbler	*Dendrocygna bicolor*
Black-bellied Whistling-Duck	Dabbler	*Dendrocygna autumnalis*
American Wigeon	Dabbler	*Anas americana*
Bufflehead	Diver	*Bucephala albeola*
Canvasback	Diver	*Aythya valisineria*
Common Merganser	Diver	*Mergus merganser*
Ring-necked Duck	Diver	*Aythya collaris*
Redhead	Diver	*Aythya americana*
Ruddy Duck	Diver	*Oxyura jamaicensis*
Common Goldeneye	Diver	*Bucephala clangula*
Lesser Scaup	Diver	*Aythya affinis*
American White Pelican	Fish eating	*Pelecanus erythrorhynchos*
Belted Kingfisher	Fish eating	*Megaceryle alcyon*
Neotropic Cormorant	Fish eating	*Phalacrocorax brasilianus*
Osprey	Fish eating	*Pandion haliaetus*
Bald Eagle	Fish eating	*Haliaeetus leucocephalus*
Double-crested Cormorant	Fish eating	*Phalacrocorax auritus*
Eared Grebe	Fish eating	*Podiceps nigricollis*
Western Grebe	Fish eating	*Aechmophorus occidentalis*
Ring-billed Gull	Fish eating	*Larus delawarensis*
Clark's Grebe	Fish eating	*Aechmophorus clarkii*
Brown Pelican	Fish eating	*Pelecanus occidentalis*

Appendix 2 (Continued)

Common Name	**Guild**	**Scientific Name**
American Coot	Marsh Bird	*Fulica americana*
Pied-billed Grebe	Marsh Bird	*Podilymbus podiceps*
Common Gallinule	Marsh Bird	*Gallinula galeata*
Ridgeway Rail	Marsh Bird	*Rallus obsoletus*
Sora	Marsh Bird	*Porzana carolina*
Killdeer	Shorebird	*Charadrius vociferus*
Greater Yellowlegs	Shorebird	*Tringa melanoleuca*
Least Sandpiper	Shorebird	*Calidris minutilla*
Western Sandpiper	Shorebird	*Calidris mauri*
Spotted Sandpiper	Shorebird	*Actitis macularius*
Lesser Yellowlegs	Shorebird	*Tringa flavipes*
Long-billed Dowitcher	Shorebird	*Limnodromus scolopaceus*
Wilson's Snipe	Shorebird	*Gallinago delicata*
Black-necked Stilt	Shorebird	*Himantopus mexicanus*
Great Egret	Wading Bird	*Ardea alba*
Great Blue Heron	Wading Bird	*Ardea herodias*
Snowy Egret	Wading Bird	*Egretta thula*
White-faced Ibis	Wading Bird	*Plegadis chihi*
Green Heron	Wading Bird	*Butorides virescens*
Black-crowned Night-Heron	Wading Bird	*Nycticorax nycticorax*
Least Bittern	Wading Bird	*Ixobrychus exilis*

APPENDIX III

R CODE USED TO BUILD A PRIORI MODELS FOR WATERBIRD GUILD ABUNDANCE AND RICHNESS MODELS

```
DABBLER1 = gam(formula = Dabbler ~AREA+URBAN, family = gaussian, data=data1)
DABBLER2 = gam(formula= Dabbler ~AREA+CULTVEG, family = gaussian, data=data1)
DABBLER3 = gam(formula = Dabbler ~AREA+EDGE, family = gaussian, data=data1)
DABBLER4 = gam(formula = Dabbler ~URBAN+CULTVEG, family = gaussian, data=data1)
DABBLER5 = gam(formula = Dabbler ~URBAN+EDGE, family = gaussian, data=data1)
DABBLER6 = gam(formula = Dabbler ~EDGE+CULTVEG, family = gaussian, data=data1)
DABBLER7 = gam(formula = Dabbler ~AREA+URBAN+ CULTVEG, family = gaussian, data=data1)
DABBLER8 = gam(formula = Dabbler ~AREA+URBAN+ EDGE, family = gaussian, data=data1)
DABBLER9 = gam(formula = Dabbler ~AREA+CULTVEG+ EDGE, family = gaussian, data=data1)
DABBLER 10= gam(formula = Dabbler ~URBAN+CULTVEG+ EDGE, family = gaussian, data=data1)

DIVING1 = gam(formula = Diving ~AREA+ URBAN, family = gaussian, data=data1)
DIVING2 = gam(formula = Diving ~AREA+EDGE, family = gaussian, data=data1)
DIVING3 = gam(formula = Diving ~AREA+PERCH, family = gaussian, data=data1)
DIVING4 = gam(formula = Diving ~ URBAN, +EDGE, family = gaussian, data=data1)
DIVING5 = gam(formula = Diving ~ URBAN, + PERCH, family = gaussian, data=data1)
DIVING6 = gam(formula = Diving ~ PERCH +EDGE, family = gaussian, data=data1)
DIVING7 = gam(formula = Diving ~AREA+ URBAN, + EDGE, family = gaussian, data=data1)
DIVING8 = gam(formula = Diving ~AREA+ URBAN, + PERCH, family = gaussian, data=data1)
DIVING9 = gam(formula = Diving ~AREA+EDGE+ PERCH, family = gaussian, data=data1)
DIVING10 = gam(formula = Diving ~ URBAN, +EDGE+ PERCH, family = gaussian, data=data1)
DIVING11 = gam(formula = Diving ~AREA+ URBAN, +EDGE+ PERCH, family = gaussian, data=data1)

Fish.eating1 = gam(formula = Fish.eating ~AREA+URBAN, family = gaussian, data=data1)
Fish.eating2 = gam(formula = Fish.eating ~AREA+EDGE, family = gaussian, data=data1)
Fish.eating3 = gam(formula = Fish.eating ~AREA+PERCH, family = gaussian, data=data1)
Fish.eating4 = gam(formula = Fish.eating ~URBAN+EDGE, family = gaussian, data=data1)
Fish.eating5 = gam(formula = Fish.eating ~URBAN+PERCH, family = gaussian, data=data1)
Fish.eating6 = gam(formula = Fish.eating ~PERCH+EDGE, family = gaussian, data=data1)
Fish.eating7 = gam(formula = Fish.eating ~AREA+URBAN+ EDGE, family = gaussian, data=data1)
Fish.eating8 = gam(formula = Fish.eating ~AREA+URBAN+ PERCH, family = gaussian, data=data1)
Fish.eating9 = gam(formula = Fish.eating ~AREA+EDGE+ PERCH, family = gaussian, data=data1)
Fish.eating10 = gam(formula = Fish.eating ~URBAN+EDGE+ PERCH, family = gaussian, data=data1)
Fish.eating11 = gam(formula = Fish.eating ~AREA+URBAN+EDGE+ PERCH, family = gaussian,
data=data1)

Rail1 = gam(formula = Rail ~AREA+URBAN, family = gaussian, data=data1)
Rail2 = gam(formula= Rail ~AREA+EDGE, family = gaussian, data=data1)
Rail3 = gam(formula = Rail ~AREA+EDGE, family = gaussian, data=data1)
Rail4 = gam(formula = Rail ~URBAN+CULTVEG, family = gaussian, data=data1)
Rail5 = gam(formula = Rail ~URBAN+EDGE, family = gaussian, data=data1)
Rail6 = gam(formula = Rail ~EDGE+CULTVEG, family = gaussian, data=data1)
Rail7 = gam(formula = Rail ~AREA+URBAN+ CULTVEG, family = gaussian, data=data1)
Rail8 = gam(formula = Rail ~AREA+URBAN+ EDGE, family = gaussian, data=data1)
Rail9 = gam(formula = Rail ~AREA+CULTVEG+ EDGE, family = gaussian, data=data1)
Rail10 =gam(formula = Rail ~URBAN+CULTVEG+ EDGE, family = gaussian, data=data1)

Shorebird1 = gam(formula = Shorebird ~AREA+URBAN, family = gaussian, data=data1)
Shorebird2 = gam(formula= Shorebird ~AREA+EDGE, family = gaussian, data=data1)
Shorebird3 = gam(formula = Shorebird ~AREA+CONNECT, family = gaussian, data=data1)
Shorebird4 = gam(formula = Shorebird ~URBAN+EDGE, family = gaussian, data=data1)
Shorebird5 = gam(formula = Shorebird ~URBAN+CONNECT, family = gaussian, data=data1)
Shorebird6 = gam(formula = Shorebird ~CONNECT+EDGE, family = gaussian, data=data1)
Shorebird7 = gam(formula = Shorebird ~AREA+URBAN+ EDGE, family = gaussian, data=data1)
```

```
Shorebird8 = gam(formula = Shorebird ~AREA+URBAN+ CONNECT, family = gaussian, data=data1)
Shorebird9 = gam(formula = Shorebird ~AREA+EDGE+ CONNECT, family = gaussian, data=data1)
Shorebird10 = gam(formula = Shorebird ~URBAN+EDGE+ CONNECT, family = gaussian, data=data1)

Wading.Bird1 = gam(formula = Wading.Bird ~AREA+URBAN, family = gaussian, data=data1)
Wading.Bird2 = gam(formula= Wading.Bird ~AREA+CULTVEG, family = gaussian, data=data1)
Wading.Bird3 = gam(formula = Wading.Bird ~AREA+CONNECT, family = gaussian, data=data1)
Wading.Bird4 = gam(formula = Wading.Bird ~URBAN+CULTVEG, family = gaussian, data=data1)
Wading.Bird5 = gam(formula = Wading.Bird ~URBAN+PERCH, family = gaussian, data=data1)
Wading.Bird6 = gam(formula = Wading.Bird ~CONNECT+CULTVEG, family = gaussian, data=data1)
Wading.Bird7 = gam(formula = Wading.Bird ~AREA+URBAN+ CULTVEG, family = gaussian,
data=data1)
Wading.Bird8 = gam(formula = Wading.Bird ~AREA+URBAN+ CONNTECT, family = gaussian,
data=data1)
Wading.Bird9 = gam(formula = Wading.Bird ~AREA+CULTVEG+ CONNECT, family = gaussian,
data=data1)
Wading.Bird10 = gam(formula = Wading.Bird ~AREA+PERCH+CULTVEG+CONNECT, family =
gaussian, data=data1)

Richness1 = gam(formula = Richness ~AREA+URBAN, family = poisson, data=data1)
Richness2 = gam(formula = Richness ~AREA+CULTVEG, family = poisson, data=data1)
Richness3 = gam(formula = Richness ~EDGE+CULTVEG, family = poisson, data=data1)
Richness4 = gam(formula = Richness ~CONNECT+CULTVEG, family = poisson, data=data1)
Richness5 = gam(formula = Richness ~EDGE+CONNECT, family = poisson, data=data1)
Richness6 = gam(formula = Richness ~EDGE+CULTVEG+CONNECT, family = poisson, data=data1)
Richness7 = gam(formula = Richness ~AREA+CULTVEG+EDGE, family = poisson, data=data1)
Richness8 = gam(formula = Richness ~URBAN+AREA+EDGE, family = poisson, data=data1)
Richness9 = gam(formula = Richness ~URBAN+AREA+CULTVEG, family = poisson, data=data1)
Richness10 = gam(formula = Richness ~URBAN+EDGE+CONNECT, family = poisson, data=data1)
```

APPENDIX IV

PREDICTIVE MAPS FOR GUILD ABUNDANCE IN SELECTED AREAS OF PHOENIX, ARIZONA

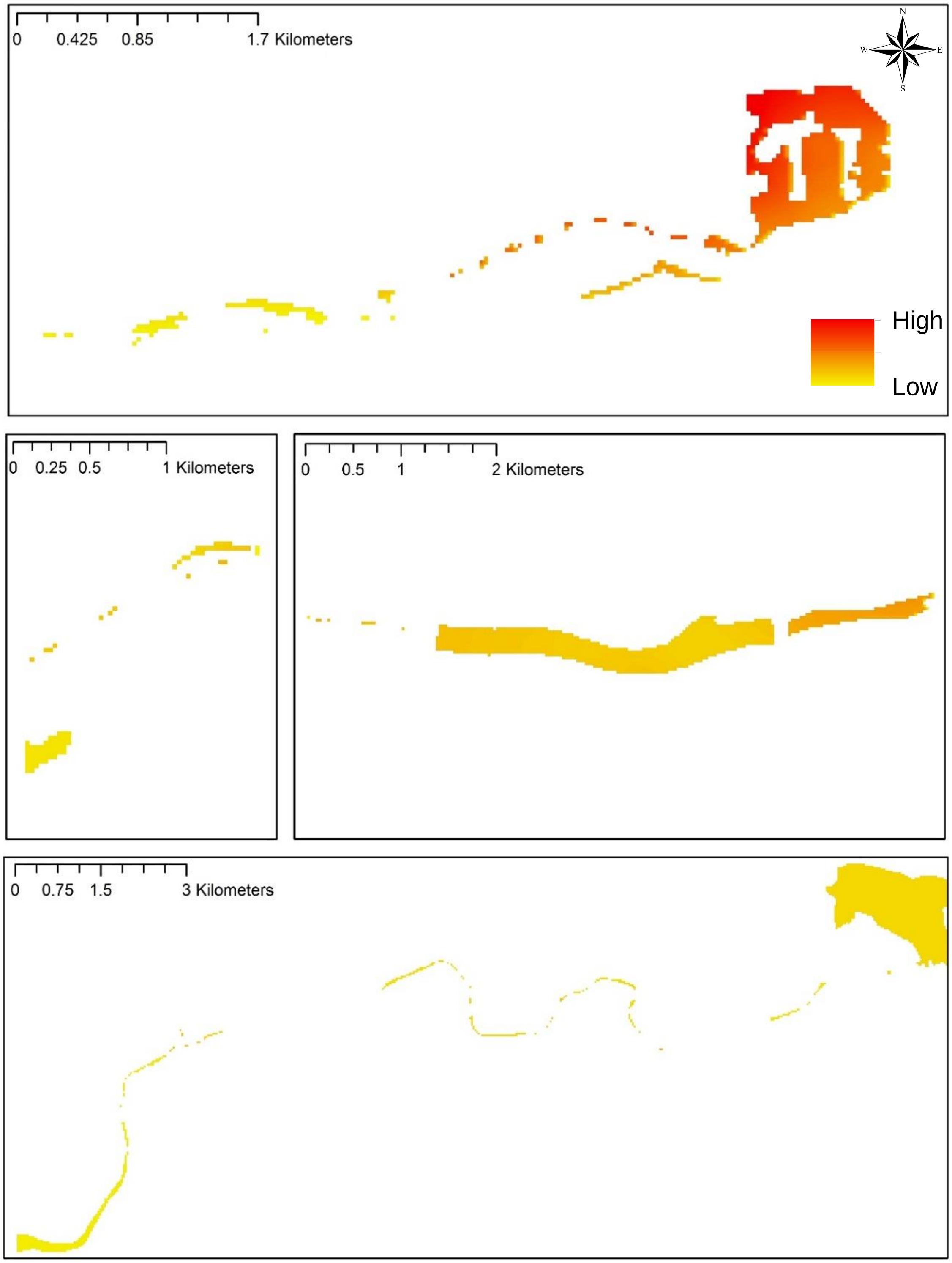


FIG A3-1. Dabbling duck guild abundance map for the Salt River study area in Phoenix, Arizona. Abundance increased with shoreline complexity, and cultivated vegetation; and showed a quadratic response to water surface area. Abundance ranged from 0 to 149.33, with relatively high maximum values as compared to the other guilds, occurring at the Tres Rios Wetlands (upper quadrant).

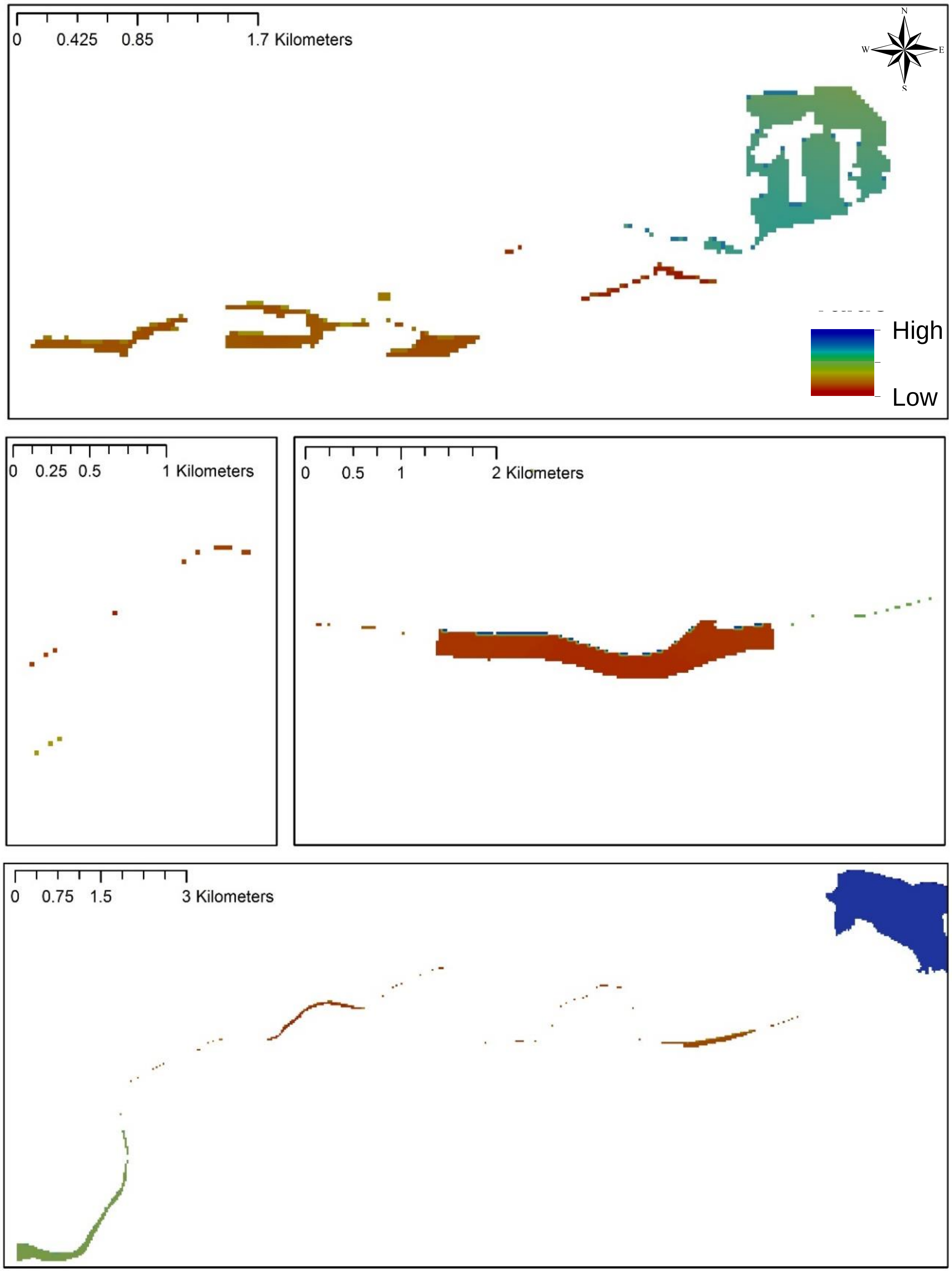


FIG A3-2. Diving duck guild abundance map for the Salt River study area in Phoenix, Arizona. Abundance increased with area, but this pattern leveled out after a certain threshold; and decreased with shoreline complexity and perching structure. Abundance ranged from 0 to 32.29.

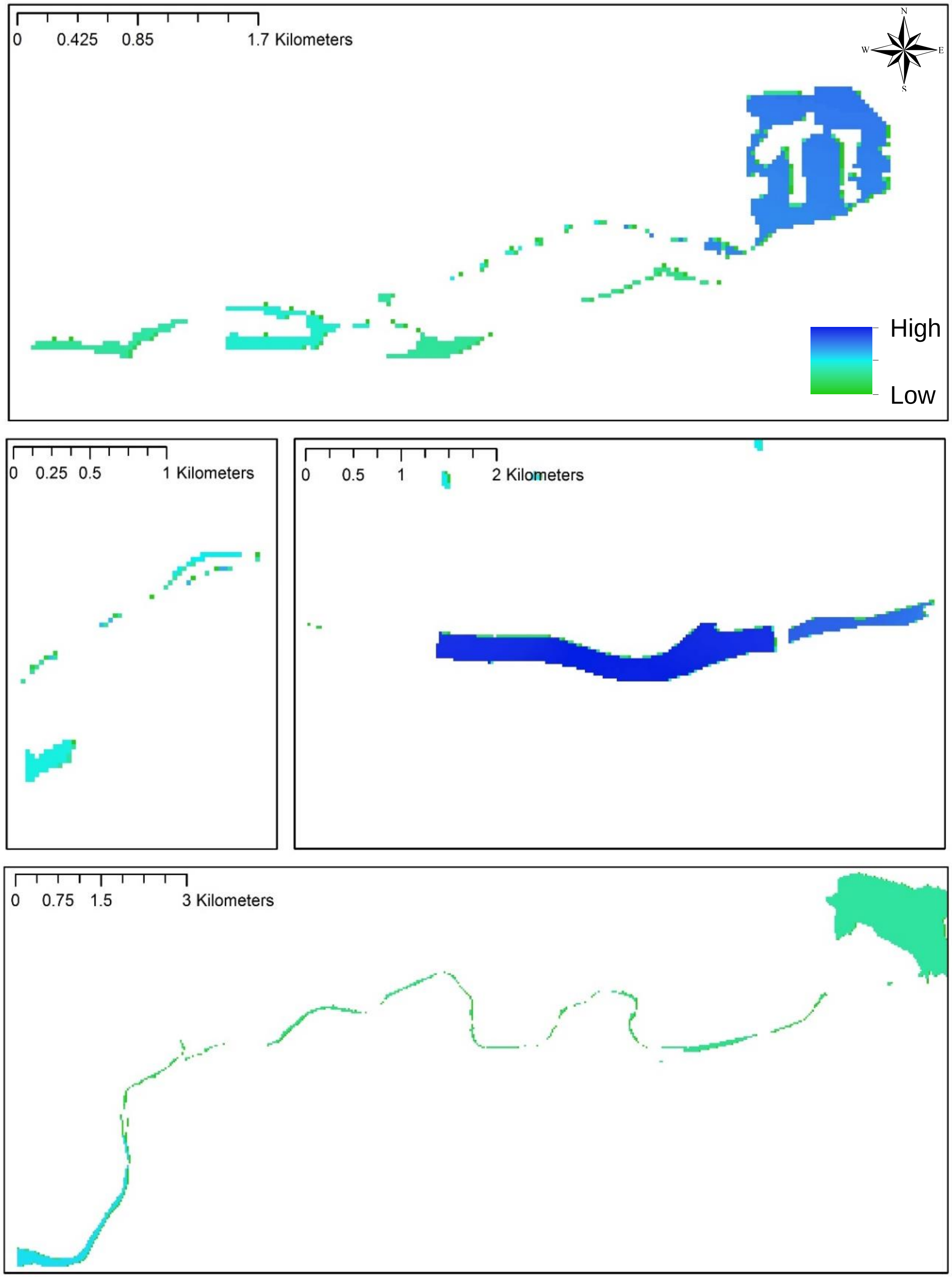


FIG A3-3. Fish-eating bird guild abundance map for the Salt River study area in Phoenix, Arizona. Abundance increased with area and perching structure; and decreased with shoreline complexity. Abundance relatively under-predicted, ranging from 0 to 18.98, with values peaking at Tempe Town Lake and Tres Rios Wetlands.

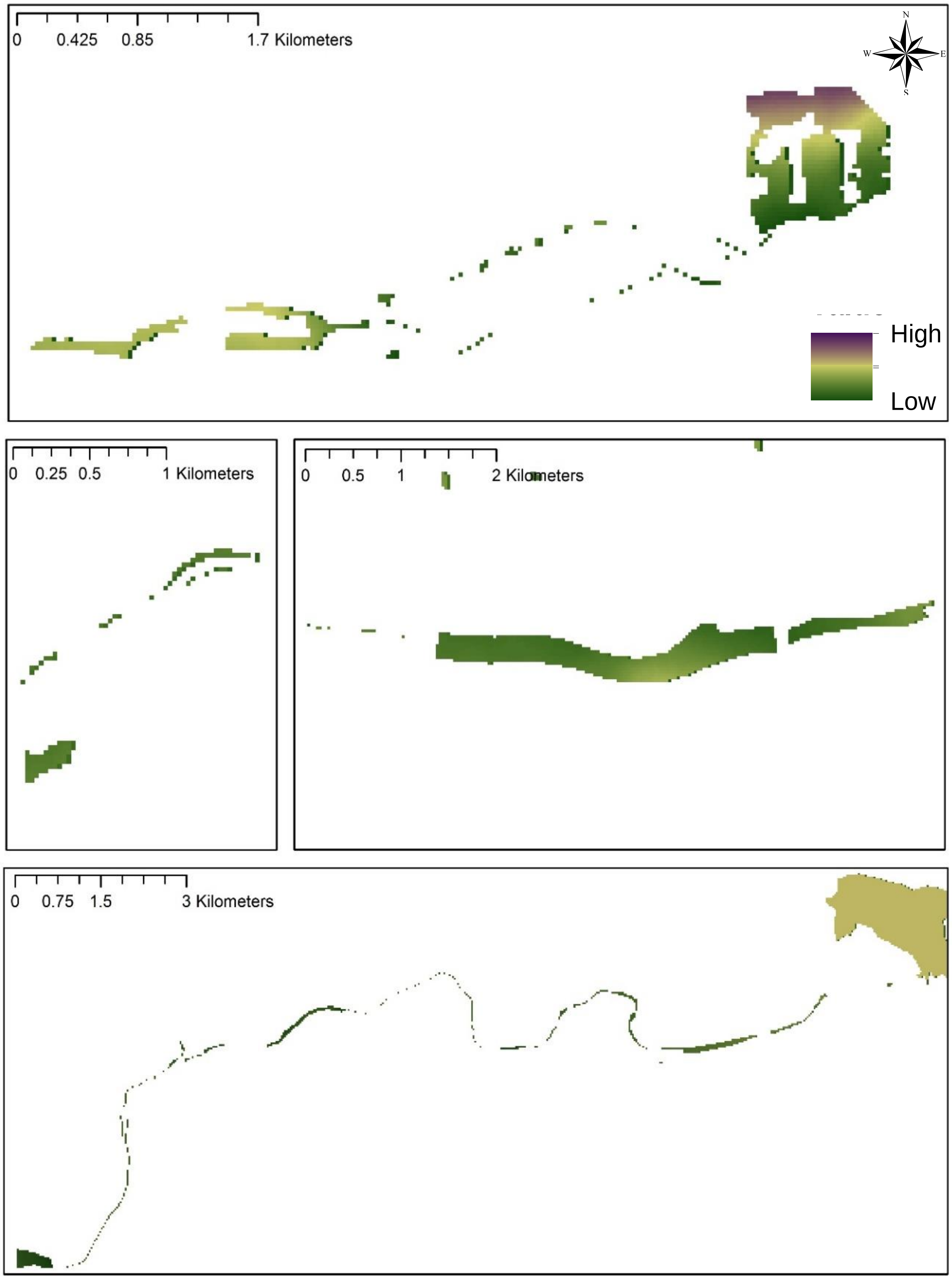


FIG A3-4. Rail guild abundance map for the Salt River study area in Phoenix, Arizona. Abundance increased with area, urbanization, and cultivated vegetation. Rails were primarily composed of American Coots. Similar to dabbling ducks, abundance ranged from 2 to 0 and peaked at Tres Rios Wetlands.

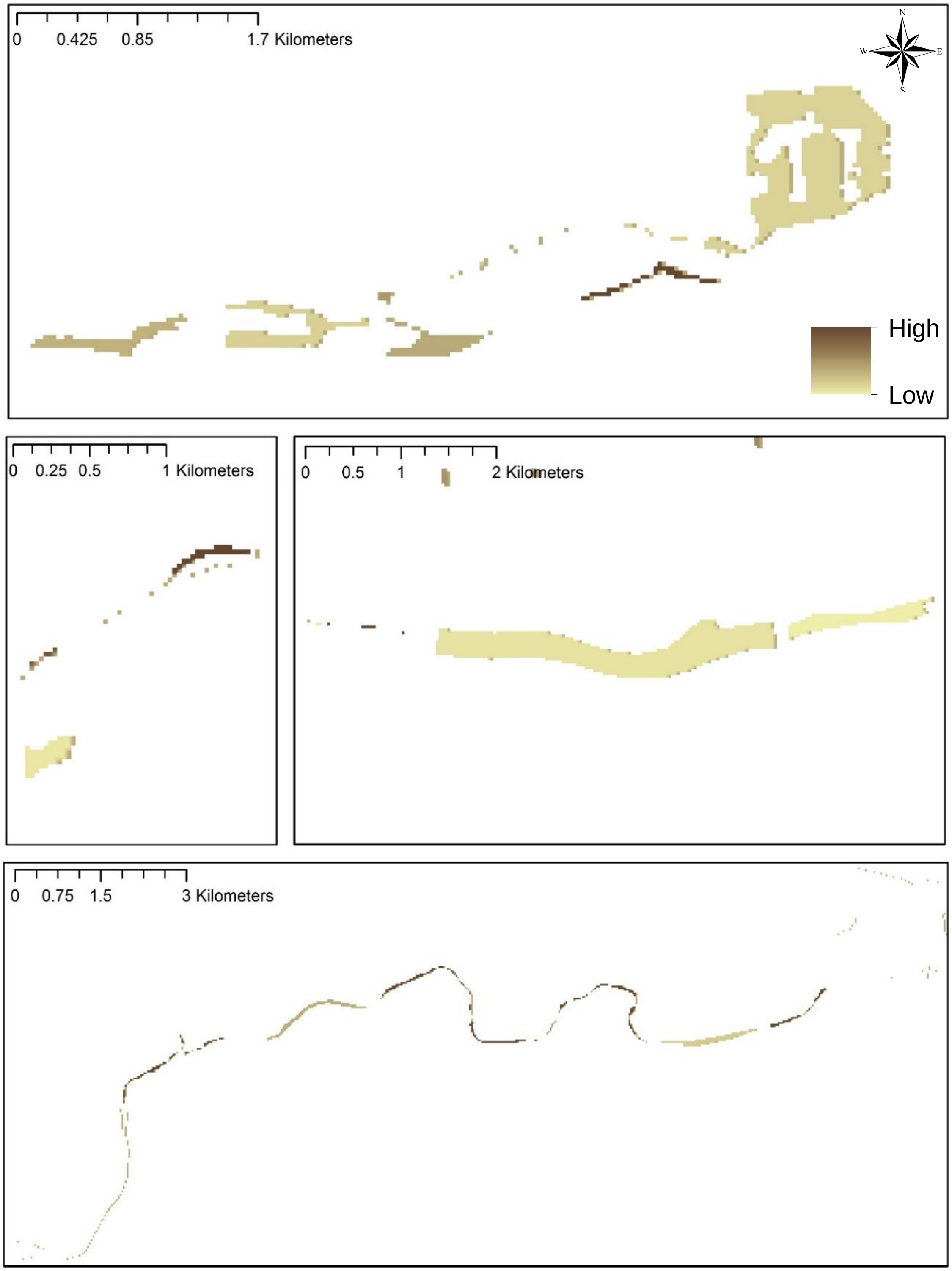


FIG A3-5. Shorebird guild abundance map for the Salt River study area in Phoenix, Arizona. Abundance increased with shoreline complexity and decreased with water area. Abundance relative to observations was over predicted and ranged from 23.61 to 0, max values were predicted over the desert length of the Salt River, which provides extended shallow habitat with ample foraging opportunities.

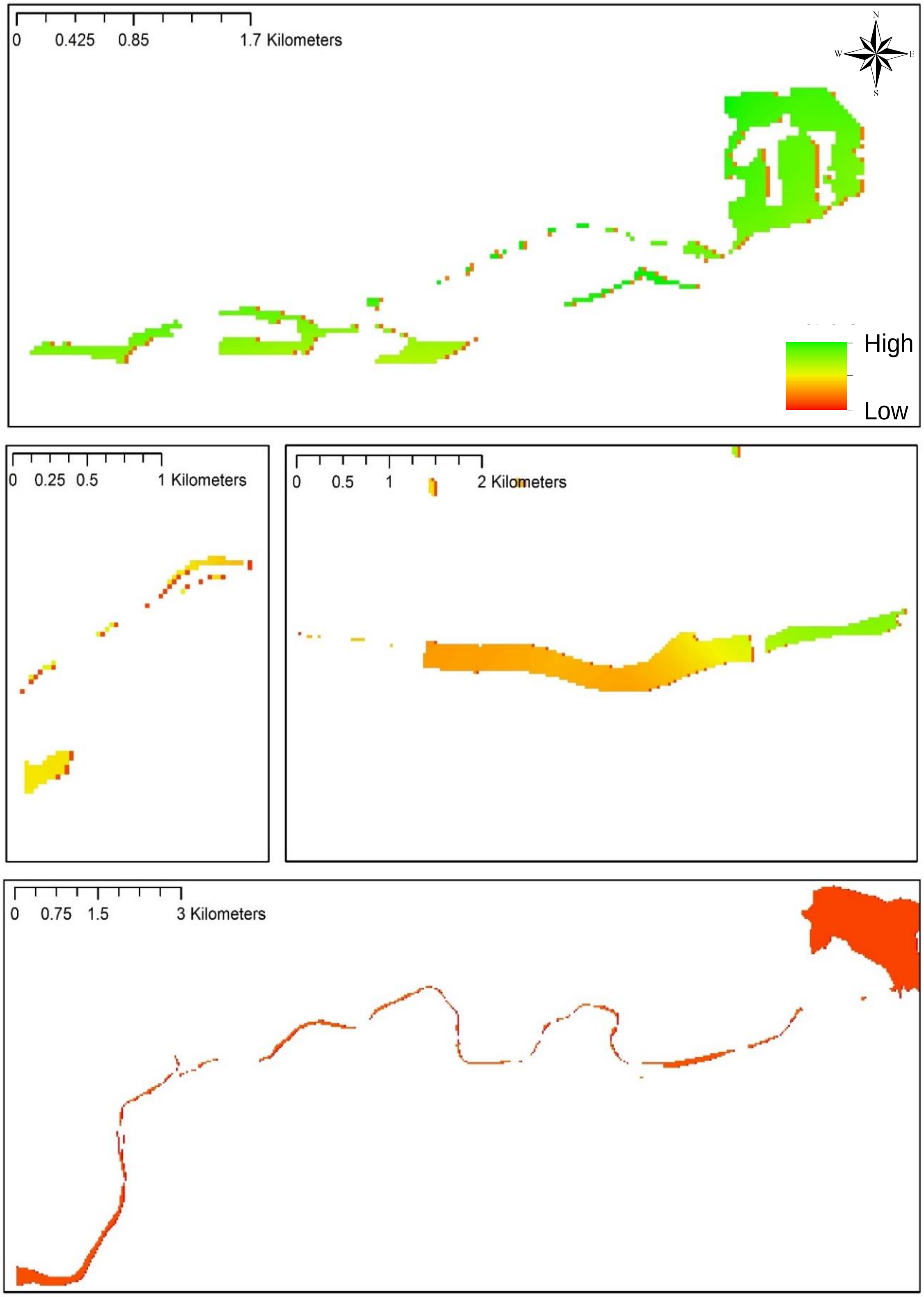


FIG A3-6. Wading bird guild abundance map for the Salt River study area in Phoenix, Arizona. Abundance increased with shoreline complexity and cultivated vegetation. Abundance ranged from 0 to 24.85 and peaked at intermediate levels of urbanization.