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Environmental Outcomes of Urban Land System Change: Comparing Riparian Design Approaches in the Phoenix Metropolitan Area

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ABSTRACT

In the face of climate change and other environmental challenges, an increasing number of cities are turning to land design to enhance urban sustainability. Land system architecture (LSA)—which examines the role of size, shape, distribution, and connectivity of land units in relation to the system's social-environmental dynamics—can be a useful perspective for examining how land contributes to the social and environmental aspects of urban sustainability. There are two gaps, however, that prevent LSA from fully contributing to urban sustainability dialogues. First, it is not well understood how urban design goals, as expressed by urban planners and other practitioners, relate to LSA and environmental outcomes. Second, most LSA work focuses on individual environmental outcomes, such as the urban heat island effect, instead of considering the broader suite of outcomes that LSA changes impact. Here, we undertake an integrated assessment of LSA impacts on surface urban heat island (based on land surface temperature), vegetation presence/health (based on NDVI), and bird biota at two riparian sites with different design intentions in the Phoenix, Arizona metropolitan area. The Rio Salado in Tempe underwent a city-led, infill redevelopment that mixed economic, recreational, and flood control design goals. The New River in Peoria experienced a more typical developer-driven urbanization. The contexts and design goals of the sites generated differences in their LSA, but only a few of these differences were sufficiently unique to contribute to divergent environmental outcomes. These differences reside in (1) the greater distribution of recreational land-covers and (2) increased surface water at the Rio Salado site compared to the New River site. Both changes are linked to land-cover patches becoming greener and cooler as well as a greater presence of waterbird and warbler species at the Rio Salado site. The distinctions between the sites provide insight for crafting design goals for redeveloping or restoring urban riparian landscapes in the Phoenix metropolitan area that are grounded in LSA. With the incorporation of additional relevant variables, especially socioeconomic ones, the research approach employed in this study provides a foundation for the assessment of other urban land system change.

1. Introduction

Urban areas cover approximately one percent of the world's land surface, house over half of the world's population, and consume seventy-five percent of the world's resources (Harrison and Pearce, 2000; Liu et al., 2014; United Nations, 2018). Their continued growth raises concerns about urban sustainability (Childers et al., 2014; Grimm et al., 2008; Seto et al., 2012; Wu, 2014) and the ways in which cities can adapt to and mitigate for the range of consequences from global environmental change, foremost climate change (Chhetri et al., 2019; Martin and McTarnaghan, 2018; Rosenzweig and Solecki, 2015). Urban land design—intentional modifications to the size and pattern of a cityscape—affects the structure and function of the environment (henceforth environmental outcomes) and is one means to mitigate and adapt to local and global environmental changes (Grimm et al., 2015; Turner et al., 2013).

As such, urban land design is increasingly of interest to research fields such as urban climatology (Golany, 1996), landscape architecture (Collinge, 1996), landscape ecology (Forman, 1995; Wu, 2013), geodesign (Goodchild, 2010; McHarg, 1992), and land system science. Each of these research fields approach design and urban sustainability with different queries, theories, and methods, but all are concerned with how design impacts the urban environment (Leemans and Groot de, 2003; Roy Chowdhury and Turner, 2019). Each fields' incorporation of urban land design is briefly reviewed below.

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Urban climatology examines the effects of the morphology of built structures and vegetation to better understand how the design of urban areas impact microscale and mesoscale climate (Oke, 1988). Urban climate research also integrates findings, such as those on air quality and the urban heat island, with the planning and design process (e.g. Coseo and Larsen, 2015; Oke, 1984; Stewart and Oke, 2012).

Landscape architecture has long examined urban design in terms of the cultural landscape, with recent attention on sustainability and design linkages to urban ecosystems (Collinge, 1996; Wines, 2000). Landscape ecology, in turn, has traditionally examined the impacts of landscape mosaics, or the composition and configuration of land units (i.e., patches), on ecosystem structure and function (Dramstad et al., 1996). These two fields have found synergies over the past several decades (Forman, 2008; Wu, 2019), with planned and designed landscapes providing field experiments to test landscape ecology hypotheses (Golley and Bellot, 1991). Nassauer and Opdam (2008) further solidified design as a central component of landscape ecology in their pattern-process-design framework. Urban ecology has followed suit (Grimm et al., 2008) by assessing the role of urban landscape mosaics on environmental outcomes (Cadenasso et al., 2013; Forman, 2014; Pickett and Cadenasso, 2008). Landscape architecture, landscape ecology, and urban ecology now call for transdisciplinary inclusion of design in research and practice (Ahern, 2013; Cadenasso and Pickett, 2013; Childers et al., 2015; Dramstad et al., 1996; Nassauer, 2012; Nassauer and Opdam, 2008; Pickett et al., 2004; Steiner, 2014).

Sharing this focus, but largely associated with spatial science, the emerging field of geodesign provides a platform for linking various landscape and land system approaches to sustainability (Huang et al., 2019; Wu, 2019). Geodesign emphasizes inclusive and iterative design in a framework that incorporates spatial technologies (i.e., models and simulations) with real-time stakeholder feedback (Steinitz, 2012).

Lastly, land system architecture (LSA) is an outgrowth from land system science (LSS) and its interest in sustainability, vulnerability, and resilience (Verburg et al., 2013). LSA examines the composition (size/area of a land cover type) and configuration (shape, distribution, connectivity of a land-cover type) of built landscapes as a result of formal and informal design—typically with a lens on its social-environmental consequences (Turner, 2010; Turner et al., 2013). LSA has many synergies with landscape ecology (Frazier et al., 2019; Vadjunec et al., 2018) and, in some cases, LSA and landscape ecology are indistinguishable in methods (Huang and Cadenasso, 2016; Li et al., 2011). Additionally, sharing concerns with morphology in urban climate research, recent LSA research has incorporated the vertical dimension of land-covers (e.g. building or tree height) (Zhang et al., 2019). We designate LSA as the variety of work across several fields of research loosely affiliated with land system science, especially urban land systems.

Emergent LSA research has largely focused on the built environment's effect on land surface temperature (LST) at a fine-grain level: cases in which 1-30 m resolution remote sensing data can be matched to the composition of land units. The composition of urban land units have been found to be the dominant driver of LST, but configuration has also proven to be significant, and joined with composition, increases the explained variance of LST (Li et al., 2016, 2012; Zhou et al., 2017, 2011).

Less is known about how urban design and configuration impact environmental outcomes beyond LST, such as flora and fauna abundance and diversity. Additionally, there is increasing interest in evaluating how composition and configuration affect multiple ecosystem services (e.g. Bennett et al., 2009; Lamy et al., 2016) especially using remotely sensed data (Clinton et al., 2018; Wang et al., 2018). Few assessments, however, have addressed the LSA of formally designed landscapes and their multiple environmental impacts in an urban context or undertaken a comparison of these impacts between developments with different design intentions (but see Turner and Galletti, 2015). Our study seeks to fill these gaps through a comparison of two urban riparian corridors that were constructed with different design intentions in the Phoenix, Arizona metropolitan area. The first landscape consists of a riverfront area in the City of Tempe that was designed to enhance community use and economic development near the historic city center. The second landscape consists of a more common, developer-led design of commercial and residential expansion in Peoria. Both sites are similar in terms of geography, environment, and climate; and they differ primarily in the role design played in their development. The overarching query of this research concerns the urban LSA and environmental outcomes generated by the design distinctions.

These concerns are addressed through three questions:

1 Given the different design intentions of the two sites, how does their LSA differ?
2 How does the land surface temperature and vegetation abundance differ between the sites? Which LSA modifications—size, shape, distribution, or connectivity—have the greatest impact on land surface temperature and vegetation?
3 How do the bird communities differ between the two sites? What role does LSA play in the bird community differences between the sites?

2. Case Study

The Phoenix metropolis is situated in the arid Sonoran Desert and is characterized by a sprawling, low-density urban form. Municipal economic growth has long been driven by annexing surrounding unincorporated land (Gerszewski et al., 2014). More recently, however, older municipalities in the center of the metropolitan area have become "land-locked" (i.e., minimal or no new land to incorporate), and their focus has turned to infill development to increase the density of economic and recreational opportunities (Gerszewski et al., 2014). In contrast, newer cities on the metropolitan fringe have the capacity to convert agricultural and vacant land for urban development. The two study sites—Rio Salado in Tempe and New River in Peoria—capture these divergent approaches to urbanization within the "land-locked" city of Tempe and along the urban fringe in the city of Peoria.

2.1. Rio Salado: Tempe, AZ

Tempe, Arizona is located approximately 14 km southeast of downtown Phoenix, has a population of over 185,000 permanent residents, and is home to the main campus of Arizona State University (ASU). Incorporated in 1894, Tempe is one of the older municipalities in the region. The Rio Salado (Salt River) flows immediately north of Tempe's downtown and the ASU campus (Fig. 1). A series of upstream reservoirs has rendered the riverbed dry for most of its extent through the metro-area; water only flows during heavy rains and when reservoirs release water.

Historically, the majority of the Rio Salado riverfront has been underdeveloped for community use, commonly serving as a site for dumping, quarrying, or industrial activities. In the 1982 Rio Salado Plan, the city of Tempe enumerated several overarching goals to develop the Rio Salado riverfront relevant to design: (1) "Encourage the optimum development of land along the Salt River"; (2) "Promote the development of outdoor recreational facilities"; and (3) "Combine the flood control with environmental design in a manner that will achieve the greatest social and economic benefits for the citizens of Tempe" (City of Tempe, 1982: 11-13). Guiding these design goals was an interest in transforming the Rio Salado from an eyesore to an economically viable and signature urban environment and, in doing so, investing in Tempe's adjacent downtown area.

In the 1990s, the city of Tempe channelized the portion of the Rio Salado within the city limits to create Tempe Town Lake and established Tempe Beach Park along the new waterfront (Elmore, 1995). The river and the riverfront park are now used for multiple social and

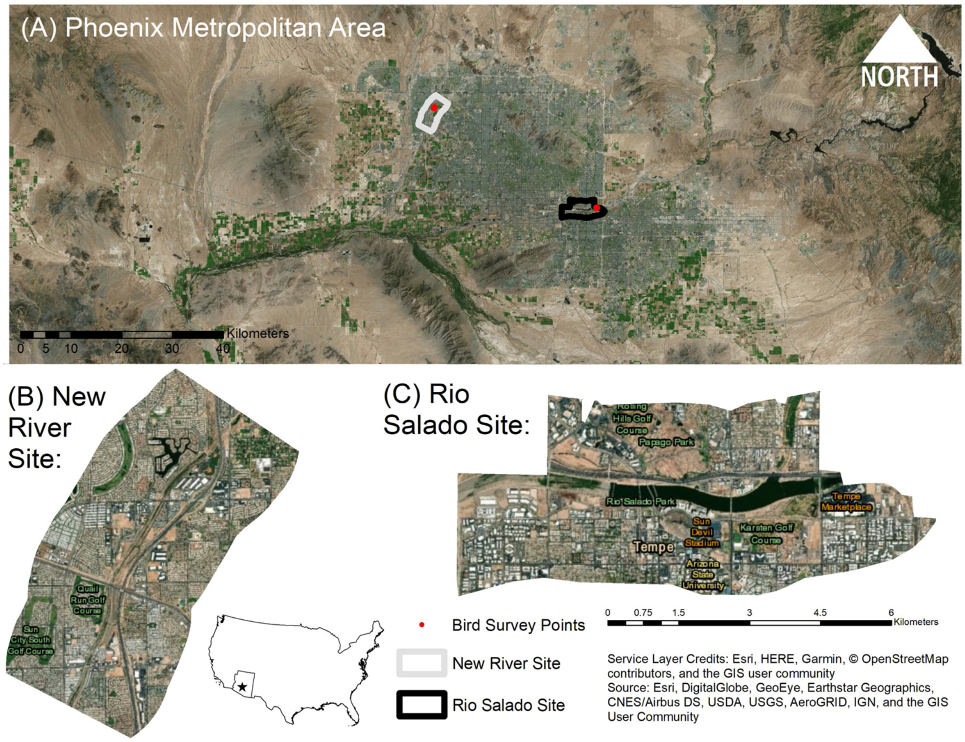

Fig. 1. (A) Study sites and location of bird surveys in the Phoenix Metropolitan area, Arizona, USA. 2019 land cover from high resolution imagery at (B) New River and (C) Rio Salado sites.

cultural events, such as concerts, festivals, major races and triathlon competitions. Within the park are multi-use paths that stretch along the riverfront into neighboring municipalities. Significant development, foremost high-rise commercial office buildings and apartment-condo units, continue to be built around the lake today in concert with the development of ASU, which possesses a large portion of the river's south bank.

2.2. New River: Peoria, AZ

Peoria, Arizona is located approximately 22 km northwest of downtown Phoenix. It is situated on the western most edge of Maricopa county (the county in which much of the Phoenix metropolitan area resides) with a small portion of the city boundaries extending west into Yavapai county. Peoria was incorporated in 1954 and has a current population of over 168,000 people. The city has seen rapid population growth since the 1990s and is expected to continue growing faster than both the Phoenix area and the state averages (City of Peoria, 2014). The New River crosses the southeastern portion of Peoria and is an intermittent stream that flows only during heavy rains. Just outside of Peoria's boundaries it joins the Aqua Fria River (also intermittent), which enters the Gila River just west of the Rio Salado-Gila connection on the southwest side of the Phoenix metropolitan area (Fig. 1).

The New River development in Peoria, led by commercial developers, constitutes a common, contemporary use of riparian space. The aim was to expand the commercial and housing areas of Peoria, while protecting this development from intermittent flood events. The area directly around the riverbed (60-150 m on either side) remains largely undeveloped (i.e., desert soil and native vegetation) or contains green infrastructure resistant to flood impacts. A multi-use trail runs along the banks of the dry riverbed. At the north end of the study area is Rio Vista Community Park. At 54 acres it is the third largest park in Peoria (City of Peoria, 2014). It has recreational fields, picnic areas, a playground, and a community recreation building (City of Peoria, 2014).

3. Methods

3.1. Site Selection

The portion of the Rio Salado riverfront examined in this study constitutes an area 1.5 km on either side of the former perineal river and extends 7 km east-west across northern Tempe (Fig. 1). The 1.5 km buffer to the north and south of the river includes a previously established bird survey site—part of the Central Arizona-Phoenix Long-Term Ecological Research (CAP LTER) network (Bateman et al., 2017)—and was delineated to capture both the built and unbuilt parts of the region. The eastern and western bounds of the study area are demarcated by the limits of the city of Tempe, as only land within the jurisdiction of the city of Tempe's development project is included in the analysis. The boundary of the New River study area is 3 km wide and 6.5 km in length to match the approximate dimensions and area of the Rio Salado site. Within the 1.5 km buffer from the New River's banks is a second CAP LTER bird site as well as both built and unbuilt lands.

3.2. Base Data and Variables

Three principal data sources were employed to generate the variables in this study: Landsat 5 satellite images, land use/land cover (LULC) classifications, and bird community surveys from CAP LTER (Fig. 2).

3.2.1. Land Use/Land Cover (LULC) Classification and Landscape Metrics

The land-cover data used to quantify LSA change are based on 30 m classifications of Landsat TM 5 imagery (Zhang and Li, 2017). Every five-year increment from 1985 to 2010 was classified using change vector analysis from the supervised object-based classification of the 2010 image (see Zhang and Li, 2017 for full details), resulting in six sets of land cover classifications (n = 6). The overall accuracy of the classification is 92.1%. The original eleven classes have been aggregated to five—water, built-up, crop, vegetation, and desert/bare soil.

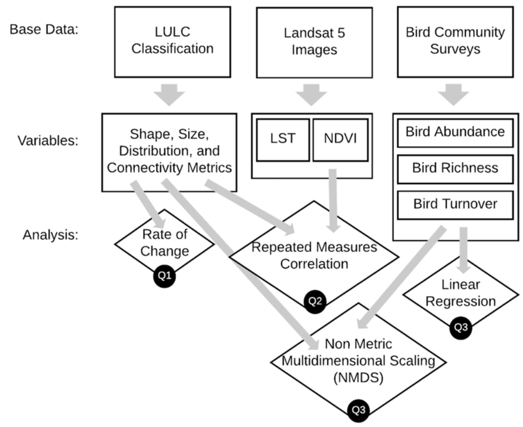

Fig. 2. Methodological workflow. Input data are represented in boxes along the top row, intermediate data processing in boxes in the middle row, and analysis in the diamonds along the bottom. The black circles at the bottom of the diamond denotes the corresponding research question.

Landscape metrics were calculated for each of the five land cover classes. Landscape metrics are algorithms that quantify the spatial structure of land-cover patterns—primarily composition and configuration—within a geographic area (Frazier, 2019). Landscape metrics typically rely on land units, referred to hereafter as patches, as the fundamental building blocks for computation. Patches represent relatively homogenous areas of land-cover that differ from their surroundings (McGarigal et al., 2012). We use patches as our unit of assessment (as opposed to larger parcel boundaries) because in urban areas, patches tend to be small and heterogeneous within parcel boundaries.

A suite of landscape metrics was selected to quantify land-cover composition and configuration based on correspondence with the four components of LSA: size, shape, distribution and connectivity (Turner et al., 2013). Size is the relative extent of an area of a particular land cover. Shape is the form of an area of a particular land cover (i.e., elliptical, rectilinear) and also considers the complexity of the land cover's boundaries (Connors et al., 2013). Distribution is the spatial arrangement (adjacency) of land-cover types, such as random, aggregated, or uniform (Gustafson, 1998). Connectivity is the linking, or lack thereof, between land covers of similar ecological or social significance (Schumaker, 1996).

Four class-level landscape metrics were computed in the software program FRAGSTATS (McGarigal et al., 2012) to capture each of the four components of LSA. Percentage of Landscape (PLAND) quantifies the proportional abundance of each patch type in the landscape and represents the area or size of each land-cover class (e.g., built-up, vegetation). The median Shape Index (SHAPE_MD) is used to quantify shape. This index measures shape compactness where a value of one constitutes a square patch and higher values represent increasing complexity in shape. SHAPE_MD is calculated by taking the median of all patch-level Shape Index values for a given class (i.e., the median of the Shape Index for all vegetation patches). The Interspersion and Juxtaposition Index (IJI) is used to measure distribution. Higher values corresponds to a proportionate distribution of patch type adjacencies (i.e., equal adjacency); a value of zero means a patch type is poorly interspersed. Lastly, the median Euclidean Nearest-Neighbor (ENN_MD) is used to measure connectivity. It is calculated by measuring the straight-line distance between the center of a patch and the nearest neighboring land unit of the same class. Since the study sites are small, we are using this distance between patches as a proxy for connectivity. Like the Shape Index, ENN_MD is a class-level metric that is computed by taking the median value of all patches in a land-cover class. Increasing values constitute increasingly dispersed patterns of patches of the same class. These four metrics were chosen for their direct relationships to the components of configuration, their intuitiveness and ease of interpretation for non-experts, as well as their use in previous scholarship linking environmental outcomes to land system composition and configuration (Connors et al., 2013; Li et al., 2012) and measuring landscape change over time (Smiraglia et al., 2015). To calculate the metrics, the land-cover maps for each year were cropped to the study area with a 30 m (1 pixel) exterior buffer added to decrease edge effects (McGarigal and Marks, 1995).

3.2.2. Land Surface Temperature (LST) and Normalized Difference Vegetation Index (NDVI)

The average LST and the Normalized Difference Vegetation Index (NDVI)—an indicator of vegetation vigor—were calculated using the same cloud-less, summer time Landsat 5 Tier 1 Surface Reflectance imagery as the LULC classification. LST is regularly used to capture facets of urban climate and studies of urban landscapes (Li et al., 2016; Myint et al., 2015; Zhang et al., 2017). NDVI is used in a range of studies to measure the rudimentary character of vegetation (Fan and Myint, 2014; Qin et al., 2017), and here NDVI is used to signify the density and quality (greenness) of vegetation cover. LST was emissivity corrected using NDVI (Shen et al., 2016). To control for daily and monthly variations in temperature, relative class-level NDVI and LST values are used (i.e., water is 5 °C cooler than the study area average). Relative values were computed by taking the difference between the average class value and the average value for the entire study area on a given day. The relative NDVI value for a given class is the difference between the average NDVI of the study area and the average NDVI for all patches in a given class. The relative LST value for a given class is the difference between average LST of the study area and the average LST for all patches in a given class.

3.2.3. Bird Community Surveys

The bird survey data at the Rio Salado and New River sites (Fig. 1) contains observations of birds seen or heard for a 40-m fixed radius (fixed-radius point count) at a 15 minute interval (Bateman et al., 2017). Surveys were completed within four hours of sunrise twice annually, once during the winter (December-February) and once during the spring (March-May). One bird survey site is located near the Rio Salado and one at the New River site (Fig. 1). Observations began in 2001 and are ongoing; we used the publicly available data for 2001-2015 for our analysis (n = 14). Community-level metrics, including annual bird abundance, richness, and turnover were calculated for each of the survey sites (Banville et al., 2017). Annual abundance is calculated as the greatest number of individuals of each species observed at the site during the survey year. Annual species richness is the number of unique species found at the site during the survey period. Turnover is the percentage of species in the community that were lost or gained compared to the previous survey. Community metrics were organized and calculated using the tidyverse package in R (Wickham, 2017).

3.3. Analyses

Research question one was examined descriptively because of the small number of years for which there is LULC data (n = 6). The slopes (i.e., rate of change) of the landscape metrics for size, shape, distribution and connectivity were calculated and compared between sites across the six years of data. Both magnitude and direction of change were examined.

To answer research question two, repeated measures correlations were used to determine the relationship between the class-level landscape metrics and the class-level NDVI and LST values (rmcorr package, Bakdash and Marusich, 2017). Repeated measures correlations are preferred over a simple regression or correlation because the yearly landscape metrics and environmental outcome variables are non-independent observations (Bakdash and Marusich, 2017). For the repeated measures correlation, the association of one landscape metric with one environmental outcome is calculated with each year of data acting as the repeated measure.

For research question three, a general linear regression was used to determine how the bird community changed over time and between sites for abundance (n = 14), richness (n = 14) and turnover (n = 13), followed by an ordination of sites in species space to compare the community composition between sites and years. Abundance, richness, and turnover are the dependent variables while time and sites are the independent variables. We tested for normalcy using a Q-Q plot as well as plotted residuals and did not note heteroscedasticity. Given the small number of samples, we determined that a linear regression was appropriate to test the general trend over time.

Temporal and spatial differences in bird community composition were tested using nonmetric multidimensional scaling (NMDS) with a square-root transformation fitted to two dimensions (vegan package, Oksanen et al., 2018). NMDS is a visualization of sites in species space by maximizing the rank correlation between the distance matrix; for our analysis we used Bray-Curtis distance and the plotted distances (Clarke, 1993). Rare species—those observed in less than 10 percent of the total surveys—were removed from analysis (McCune and Grace, 2002). Dispersion ellipses were calculated based on the standard deviation of weighted averages for the three LSA survey periods (Time Period 1: 2001-2004, Time Period 2: 2005-2009, and Time Period 3: 2010-2015) and the two sites (Rio Salado and New River). We then fit the landscape metrics onto the bird community ordination to calculate the correlation and significance of each metric with the bird community. All code and documentation for the analysis is available in a GitHub repository: https://github.com/MStuhlmacher/phx-lsa.

4. Results

4.1. Question 1: Change in Land System Architecture

Research question one examines the changes in composition and configuration of land-cover patches at the sites and their resultant land covers. Despite different locations in the Phoenix metropolitan area (i.e., center vs. fringe), both sites started with a similar level of built-up land (Figs. 3 and 4). By 2010, the New River site has 18% more built-up area.

Cropland at the New River site was almost entirely urbanized and, at both sites, desert land also made up a large portion of what was eventually urbanized. A greater proportion of desert land was developed at the Rio Salado site, but approximately 26% of it was maintained, largely in desert parklands adjacent to the river (Figs. 3 and 4). The amount of vegetated land cover increased at both sites, but the Rio Salado gained more in terms of both vegetation and water.

The shape of the land covers at the Rio Salado site underwent little change and largely remained compact, with a notable exception of the addition of water in the elongated lake (Table 1). In contrast, the land-cover classes at the New River site were less compact to start and became marginally more compact as development consolidated patches of different land-cover types. Shape compactness for the crop class increases at both sites, likely a function of the decreasing amount of cropland and the consolidation of the few remaining crop patches (Fig. 3).

Distribution values show the largest differences between the sites: built-up, desert, crop, and vegetation classes have opposite trends at the two sites (Table 1). Land covers within the Rio Salado site became more interspersed, and land covers within the New River site became less interspersed. Water became more interspersed at both sites.

Desert and cropland became more isolated at both sites—likely a function of the decreasing amounts of those classes as well as the increasing interspersion of built-up lands. Water, on the other hand, was less isolated at both sites and was the only class at the Rio Salado that did not become more isolated. The built-up and vegetation land-covers increased in connectivity for the New River site, while these two land-cover classes at the Rio Salado site did not.

The contrasting design goals of the sites led to two distinctive differences. First, the city of Tempe's goal of encouraging development balanced with the goal of creating outdoor recreational spaces which led to less built-up land and more vegetation and desert land at the Rio Salado site compared to the New River site. The "recreational" (i.e., desert and vegetation) and built-up land-covers became more isolated and dispersed. Conversely, at the New River site, almost all classes became less interspersed as the development consolidated land-cover patches. Second, the creation of Tempe Town Lake to meet flood control goals constituted a major difference in land-cover composition between the two sites. The more typical means for ensuring flood-control in the Phoenix metropolitan area—in which the area in and around a riverbed is left undeveloped or only developed with land covers that are resilient to flooding (i.e. playgrounds and playing fields)—was employed at the New River site. The distinctive lake created by channelizing the Rio Salado is a function of the way in which the city tied flood control to "achieving the greatest social and

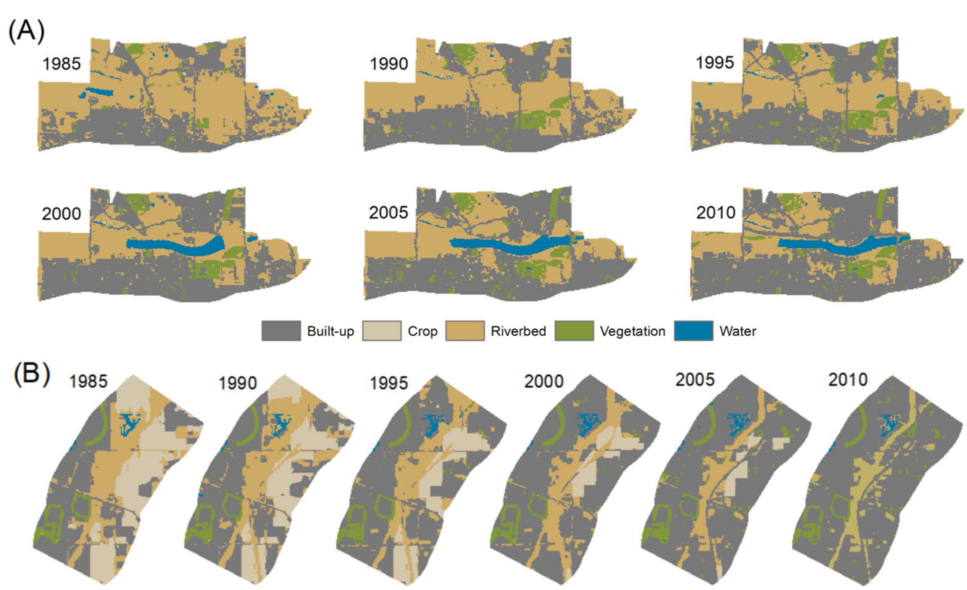

Fig. 3. Land use/land cover maps for the (A) Rio Salado and (B) New River sites.

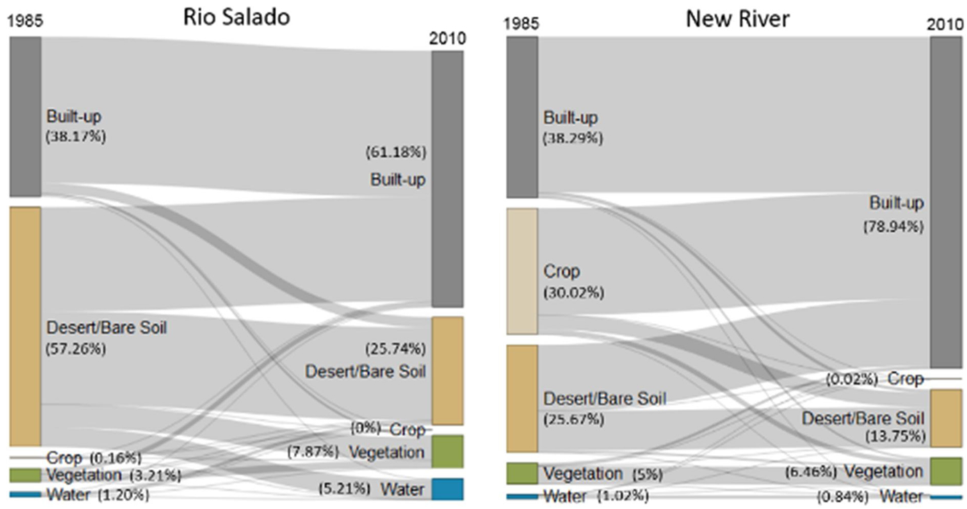

Fig. 4. Land-cover class conversion between 1985 and 2010 at the Rio Salado and New River sites. Values in parenthesis are the percentage of land a given class covers in the study area.

Table 1
Change in size, shape, distribution, and connectivity at the Rio Salado and New River sites by land-cover class. Values in parenthesis are the rate of change (slope) of the landscape metrics between 1985 and 2010.

		Built-up	Desert/ Bare Soil	Crop	Vegetation	Water
Size (PLAND)	Rio Salado	Increasing (0.805)	Decreasing (-1.182)	Decreasing (-0.005)	Increasing (0.152)	Increasing (0.230)
	New River	Increasing (1.704)	Decreasing (-0.567)	Decreasing (-1.213)	Increasing (0.077)	No Change (0)
Shape (SHAPE_MD)	Rio Salado	No Change (0)	No Change (0)	More Compact (-0.008)	No Change (0)	Less Compact (0.013)
	New River	More Compact (-0.012)	More Compact (-0.004)	More Compact (-0.005)	More Compact (-0.004)	More Compact (-0.001)
Distribution (IJI)	Rio Salado	More Interspersed (0.892)	More Interspersed (0.296)	Less Interspersed (-2.085)	More Interspersed (0.054)	More Interspersed (1.581)
	New River	Less Interspersed (-0.385)	Less Interspersed (-2.049)	More Interspersed (0.137)	Less Interspersed (-0.327)	More Interspersed (0.472)
Connectivity (ENN_MD)	Rio Salado	More Isolated (0.460)	More Isolated (0.619)	More Isolated (22.589)	More Isolated (0.228)	Less Isolated (-0.560)
	New River	Less Isolated (-1.467)	More Isolated (0.705)	More Isolated (2.892)	Less Isolated (-6.269)	Less Isolated (-3.372)

Note: Summary statistics (mean, area weighted mean, median, range, standard deviation, and coefficient of variation) for the patch-based metrics are presented in Appendix A.

economic benefits for the citizens of Tempe" (City of Tempe, 1982: 11-13). The Rio Salado in Tempe now serves as a focal point for tourism and large-scale community events.

4.2. Question 2: Land Surface Temperature, Vegetation Abundance, and LSA Change

Research question two examines the differences between NDVI and LST at the two sites and asks which LSA modification—size, shape, distribution, and connectivity—had the greatest impact on NDVI and LST. Figs. 5 and 6 present NDVI and LST values from two Landsat scenes in early August in 1985 and 2010 in order to visualize the spatial distribution of these values within the study sites. August 8th, 1985 and August 13th, 2010 were selected from the available cloudless summer images based on their proximity in date and because they are similar to the monthly average minimum and maximum temperatures for the area according to the Global Historical Climatology Network Daily Database (Menne et al., 2012b, 2012a).

Overall, NDVI increased at the Rio Salado site and decreased at the New River site (Fig. 5). The New River site had higher NDVI values in 1985 due to the presence of large tracts of farmland, but NDVI declined by 2010 as those tracts urbanized. Both sites see pockets of greater NDVI with the addition of small, verdant parks and residential landscapes.

LST increased at both sites between 1985 and 2010, and the average August daytime LST reached approximately 46 °C in 2010 at both sites (Fig. 6). The increase in temperature at both sites can be attributed to the overall urbanization occurring within and outside the study area boundaries (i.e., urban heat island effect) and, perhaps, climate change. In 1985 and 2010, areas with water and vegetation were cooler at both sites, and built-up areas had the highest LST. The New River site was cooler in 1985 and experienced a much greater increase in temperature than the Rio Salado site—partially attributable to the loss of cropland and gain in built-up area.

Examining the impact of configuration on NDVI and LST, we find that only shape and distribution had statistically significant relationships with these two environmental variables (Fig. 7). Size and connectivity did not have statistically significant relationships with NDVI and LST so are not presented here.

At the Rio Salado site, patches that were interspersed were greener (r_{rm} = 0.45, p = 0.024) and cooler (r_{rm} = -0.79, p = 2.4e-06) compared to the site average. This relationship was determined considering

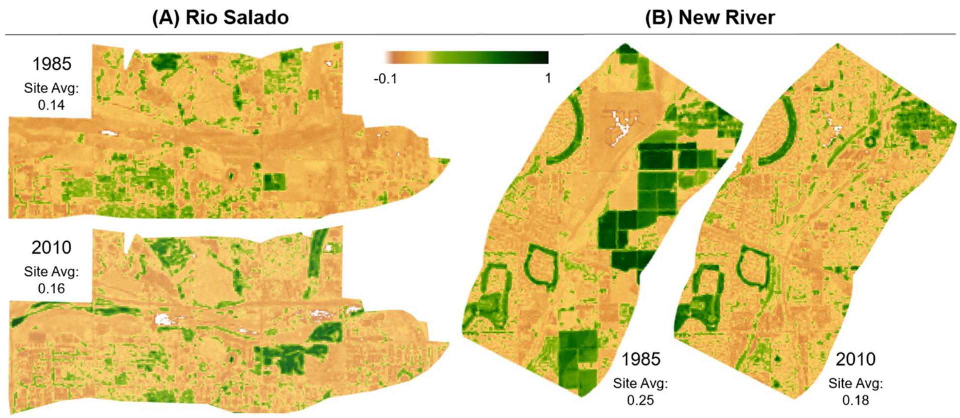

Fig. 5. Normalized Difference Vegetation Index (NDVI) maps for the (A) Rio Salado and (B) New River sites in August 1985 and 2010. Average NDVI for the whole study area is presented below the year label. Agricultural lands, as well as golf courses and traditional (mesic) residential landscaping have the highest values while water has negative values.

all land classes but was largely driven by the built-up, crop, and water classes (Fig. 7). At the New River site, patches that were more compact were greener (r_{rm} = 0.46, p = 0.017) and cooler (r_{rm} = 0.4, p = 0.044) compared to the average. Overall, the statistically significant relationships were most often driven by the built-up, crop, and water classes with riverbed and vegetation having a smaller range of values. Shape and LST had inverse relationships at the two sites. There was very little change in the shape of patches at the Rio Salado site, so the relationship was largely driven by the only land-cover classes that did change (water and the crop). Thus, more weight should be given to the New River shape result—that more compact patches are cooler—because it has a greater number of non-zero values.

Overall, there were moderate differences between the sites in terms of NDVI and LST. NDVI at the Rio Salado site increased marginally, while NDVI at the New River site decreased dramatically (largely owing to the urbanization of cropland). LST for both sites rose, ending at approximately the same average temperature. The New River site experienced a larger increase in temperature, but it was approximately 2.5 °C cooler than Tempe in 1985. The repeated measures correlation indicates that shape and distribution have a statically significant relationship with NDVI and LST, while size and connectivity do not. The small number of years examined in this assessment limit the conclusions we can draw with the repeated measures correlation, but the results provide context about the effect of landscape metrics as well as the classes that drive the relationships between landscape metrics and NDVI/LST. Water, for example, is a driver in all of the correlations presented.

4.3. Question 3: Bird Community and LSA Change

Research question three evaluates bird community differences between the two sites and the role that LSA played in these differences. Bird community abundance, richness, and turnover declined at both sites (Fig. 8), but abundance is the only metric for which there was a statistically significant difference between the two sites (F = 4.36, P = 0.04).

Abundance values started higher at the New River site, likely a function of the nearby undeveloped desert and agricultural land. The steep decline in abundance, from approximately 100 to approximately 40 over the course of fourteen years, is attributable to accumulative effects of rapid land-use change and urbanization on the urban fringe. The Rio Salado site, in the urban center, had lower abundance in 2001 but was more stable, potentially due to the addition of water and vegetation classes, which could provide consistent resources to the bird community there. The two sites appear to be nearing similar levels of abundance over time, following a larger trend in the Phoenix metro area where riparian bird communities are shifting toward urban dwelling species (Banville et al., 2017).

Differences between site type and temporal shifts in the bird community (Non-metric multidimensional scaling - NMDS stress = 0.23; fit R^2 = 0.95) is evidenced in the unconstrained ordination of sites in species space (Fig. 9). Temporal shifts are displayed on the x-axis, with lower x-values representing earlier survey years (R^2 = 0.32, P = 0.001). Over time, the species composition at the sites became more similar. Site differences are displayed on the y-axis, with negative y-values representing the New River site and positive y-values representing the Rio Salado site (R^2 = 0.36, P = 0.0001). We found that the Rio Salado supported a different bird community than it might have if it followed an urbanization trajectory similar to the New River site (Fig. 9). The Rio Salado site supported bird species that require aquatic habitat, as well as warbler species, likely due to the prevalence of semi-restored, perennial riparian habitat (Bateman et al., 2015). Conversely, terrestrial bird species and desert specialist species were more prevalent at the New River site. Appendix B contains a table with the four-letter alpha

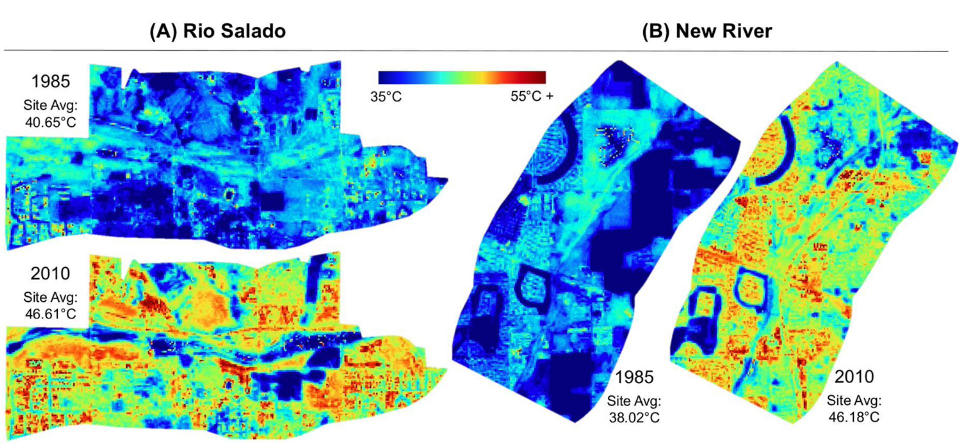

Fig. 6. Land Surface Temperature (LST) maps for the (A) Rio Salado and (B) New River sites in August 1985 and 2010. Average LST for the whole study area is presented below the year label. Color palette was determined by stretching the values within 2.5 standard deviations of the Rio Salado 2010 mean (SD = 4.7 °C). Agricultural lands, as well as golf courses and water bodies, are cool while built-up surfaces, especially in 2010, are hot.

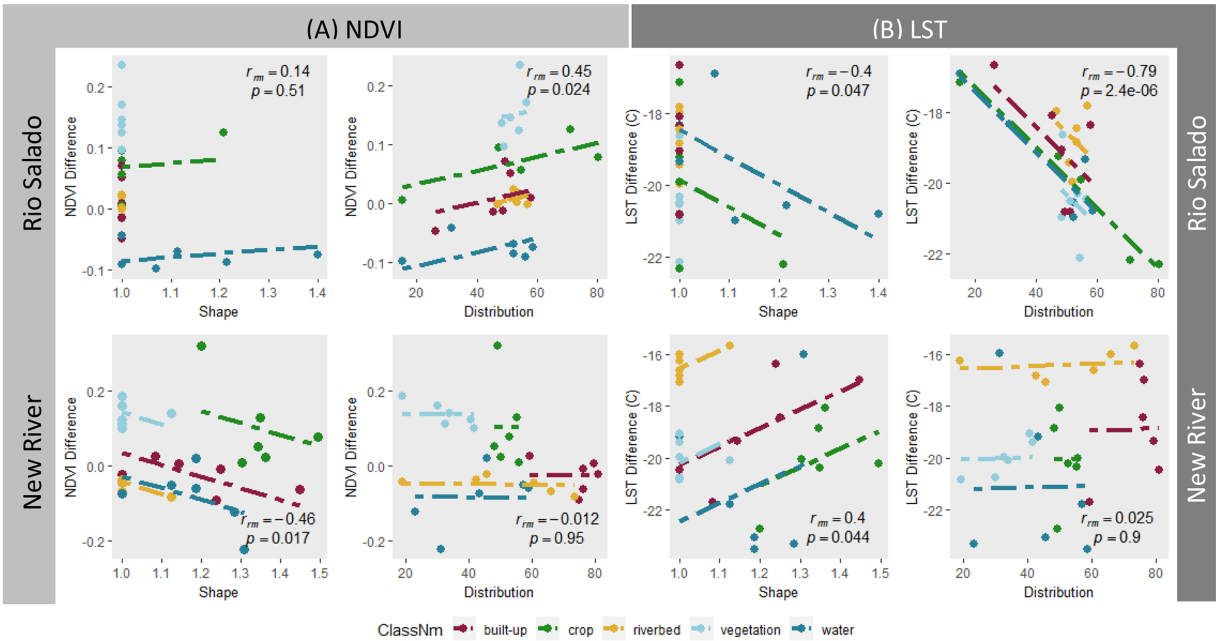

Fig. 7. Repeated Measures Correlation graphs for the class-level landscape metric values and environmental variables at the Rio Salado and New River sites. Each point represents one year of data, and the colors denote the classes. (A) is the relationship between class NDVI difference (y-axis) and class shape or distribution values (x-axis). Class NDVI difference is the difference between the average NDVI of the site and the average NDVI for all patches in a given class. Positive y-axis values indicate greater greenness compared to site average. (B) is the relationship between class LST difference (y-axis) and class shape or distribution values (x-axis). Class LST difference is the difference between the average LST of the site and the class average LST. Negative y-axis values indicate that the patches in a given class were cooler than the site average.

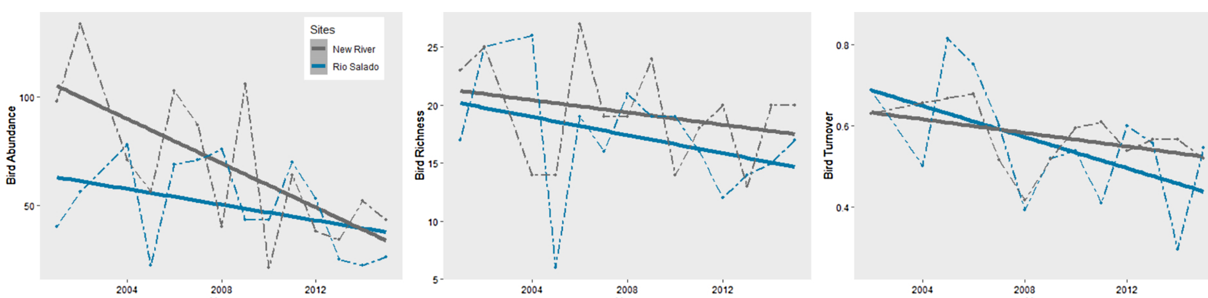

Fig. 8. Bird Community Metrics. The dashed lines are the raw data, the solid lines represent the linear regression slope for the community metric (abundance, richness, turnover) at the given site from 2001 to 2015.

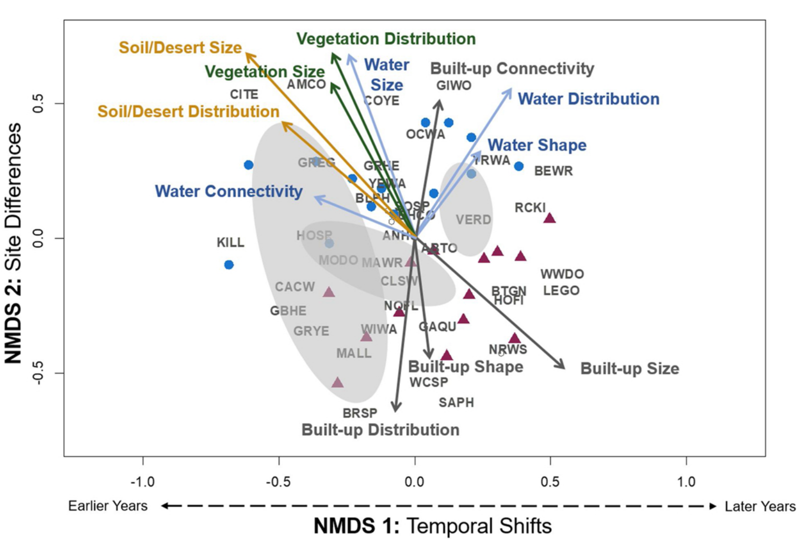

Fig. 9. Non-metric multidimensional scaling (NMDS) visualizing the temporal and spatial relationship between bird species, and the LSA components of size, shape, distribution, and connectivity. The blue circles (Rio Salado) and maroon triangles (New River) are the sites over time, arranged in species-space with bird-species labeled by their 4-letter alpha codes. See Appendix B for corresponding species names. Vectors reflect the strength and direction of the LSA components; only statistically significant ($P < 0.05$) vectors are presented. Site differences are reflected by the y-axis; vectors related to Rio Salado are in the upper portion (positive numbers), vectors related to the New River site are in the lower portion (negative numbers). Grey ellipses represent centroids for the three time periods (Time Period 1: 2001-2004, Time Period 2: 2005-2009, and Time Period 3: 2010-2015) along the x-axis. Positive x-axis numbers refer to earlier time periods beginning in 2001, while negative numbers refer to later time periods ending in 2015.

code, common name, and scientific name for all bird species in our analysis.

Water was one of the most important land-cover classes separating the sites in terms of habitat. All landscape metrics for the water class were significantly related to the bird community at the Rio Salado: water size ($R^2 = 0.73$, $P = 0.001$), water connectivity ($R^2 = 0.24$, $P = 0.022$), water shape ($R^2 = 0.28$, $P = 0.025$), and water distribution ($R^2 = 0.52$, $P = 0.001$).Conversely, built-up patches were emphasized in relationship to the bird community at the New River site: built-up size ($R^2 = 0.71$, $P = 0.001$), built-up shape ($R^2 = 0.34$, $P = 0.007$), and built-up distribution ($R^2 = 0.63$, $P = 0.001$). Built-up connectivity was positively and significantly related to the Rio Salado bird community ($R^2 = 0.44$, $P = 0.003$). Consistent with the role of urbanization in the convergence of the bird community make-up over time, built-up lands are more significant in the later years of the analysis, while the soil/desert and vegetation classes are significant for earlier years. Two of the four vegetation landscape metrics were significantly related to the bird community at the Rio Salado site: vegetation size ($R^2 = 0.48$, $P = 0.002$), and vegetation distribution ($R^2 = 0.52$, $P = 0.001$) along with soil/desert size ($R^2 = 0.74$, $P = 0.001$) and distribution ($R^2 = 0.52$, $P = 0.001$).

In answer to research question three, only the bird abundance trend was statistically different between the two sites. Bird abundance at the New River site was higher to begin with but appears to be nearing similar levels to that of the Rio Salado over time. The abundance trend at the Rio Salado was more stable, but still in decline. In terms of the role that LSA plays in the bird community differences between the sites, the interspersed patches of desert and vegetation noted above were also found to be significant in their relationship with the bird community at the Rio Salado.

The bird community's relationship with water and built-up land was even more pronounced; size, shape, distribution and connectivity were all significant for the water and built-up classes at the Rio Salado site. The differences in the sites' bird communities is attributable to the presence of desert, vegetated areas, and water at the Rio Salado site (more water bird species) and built-up areas at the New River site (more terrestrial species). Despite these differences, the bird communities' species composition at both sites—depicted by the three grey ellipses—became more similar over time, a trend mirrored in the larger metro-area (Banville et al., 2017).

5. Discussion

The distinctive design goals of Rio Salado generated various differences in LSA compared to the developer-led urban expansion at the New River site. Only two LSA differences, however, were sufficiently unique to lead to divergent outcomes for the environmental variables examined. First is the difference between the sites in terms of configuration—specifically the distribution of recreational land-cover classes. Second is the large composition change caused by the addition of Tempe Town Lake at the Rio Salado site.

5.1. Configuration

Among the four components of LSA—size, shape, distribution and connectivity—the differences in the trajectories of the two sites were greatest in terms of distribution (i.e., the interspersion or adjacency of patches of the same class among other classes). The Rio Salado's built-up, vegetation, and desert land-cover patches became more interspersed as the area developed (Table 1), which had implications for the site's surface temperature, greenness, and the bird community. The repeated measures correlations and NMDS indicate that distribution has a statistically significant relationship with each of the examined environmental outcomes: greater interspersion was related to greener and cooler conditions (Fig. 7) and the distribution of desert, vegetation, and water patches were related to the bird community at the Rio Salado site (Fig. 9).

The importance of land-cover distribution in distinguishing the Rio Salado site has potential planning implications. Developers, planners, and other land design professionals must consider the surrounding context of the land covers with which they are working (Connors et al., 2013). The value of considering the composition and configuration of landscapes as a whole is well understood (Huang et al., 2019; Nassauer and Opdam, 2008; Steinitz, 2012; Turner, 2016; Vadjunec et al., 2018), and our findings on the importance of distribution highlight this further. Distribution, of all the components of LSA, is a measure of configuration strongly tied to the surrounding landscape.

Notably, our findings about the primacy of distribution are counter to much of the previous LSA literature that has found composition to be the primary driver of LST (Li et al., 2017, 2012; Zhou et al., 2017, 2011), although at least one LST study (Li et al., 2016) also found configuration to be more important than composition. Additionally, the finding that interspersed patches are greener and cooler is contrary to some previous findings on pattern and LST (Fan et al., 2015; Li et al., 2017, 2012; Myint et al., 2015). Configuration relationships, however, have been found to vary in magnitude, significance, or direction based on the location of the case study (Zhou et al., 2017), the scale (Connors et al., 2013) and the land-cover class evaluated (Myint et al., 2015). The variation in scale may partly be explained by the Phoenix metro-area findings that clustered green space enhances local cooling but interspersed patches lead to greater regional cooling (Zhang et al., 2017).

Our findings on the role of distribution may be influenced by our methodology. The majority of previous research has examined one class (i.e., greenspace or impervious surface) at a time (Fan et al., 2015; Li et al., 2012; Zhang et al., 2017). We chose to use a repeated measures correlation, which considers the relationship between NDVI and LST with all land-cover classes together but also identifies which classes drive the relationship. Methodologically, this mirrors the need for thinking about and planning land-cover change in context. The repeated measures correlation may be more appropriate than examining one class in isolation because land-cover classes co-exist in a landscape, and any environmental impacts are a response to a mosaic of heterogeneous land covers. This is especially the case in urban green spaces, which are functional components of urban ecosystems that interact spatially with surrounding land-covers (Noss, 1987; Tian et al., 2011).

5.2. Composition

The addition of Tempe Town Lake—a major change of land composition—allowed the Rio Salado site to support waterbird and warbler species. The New River site, with its greater amount of built-up land cover, supported more terrestrial bird species (Fig. 9). This aligns with multi-site evaluations in central Arizona which have found land-change to be a dominate factor in changes in species composition over time, leading to more unique species between land-use types (Allen et al., 2019). Water was also one of the most influential classes in determining the relationships of the repeated measures correlations (Fig. 7).

Additionally, abundance declined less precipitously at the Rio Salado site (Fig. 8), which may be attributable to the lower levels of abundance to begin with or the addition of water. In the Phoenix metro-area, abundant surface water can lead to higher levels of bird diversity than the outlying desert (Andrade et al., 2018). The lake creation may have slowed the decline of bird diversity at the Rio Salado, but diversity and abundance at the two sites seem to be converging. These trends reflects the larger, regional scale shifts in which the riparian bird community is shifting toward urban dwelling, resident species (Banville et al., 2017) along with a decline of desert species in the southwest (Iknayan and Beissinger, 2018; Warren et al., 2019) and the broader North American avifauna decline (Rosenberg et al., 2019).

5.3. Summary

In summation, despite distinctive design goals and corresponding differences in the LSA of the two sites, only moderate differences in the environmental outcomes were identified. Our findings are consistent with Turner and Galletti (2015), who also found modest improvements in the environmental performance of an urban development that employed purposeful environmental design. It follows that one of the major policy and planning implications of our study is that existing methods from LSA (and similar landscape design fields) can inform sustainable urbanization by providing quantifiable metrics for measuring a range of environmental outcomes (Turner, 2016; Turner et al., 2013; Turner and Galletti, 2015; Wu, 2019). There is more to be done, however, before LSA methods are regularly operationalized in land-based decision making. In this study, we focused on environmental consequences, but recognize that the inclusion of the social dimensions of LSA (e.g., housing costs or proximity to recreation spaces) would alter our results. Future LSA work requires collaboration with government officials, policy makers, planners, developers, and other stakeholders to identify and monitor relevant socio-environmental desired outcome variables and frame them in terms of their contribution to neighborhood, city, or regional sustainability goals (Aragon et al., 2019; Groffman et al., 2017).

5.4. Limitations

One limitation of this study is the effect that the selection and the extent of the two case study sites may have on the results. The Rio Salado's urbanization is an infill development, while the New River site urbanized the fringe of the metropolitan area. These contrasting sites were chosen to ensure divergent design intentions, systematic bird survey data, and riparian locations. The initial differences in the land systems of the two sites, however, confounds our ability to assess environmental change because they do not begin with similar bird communities, NDVI, or LST values. Moreover, while the boundaries of each site were selected to be similar in area and inclusive of surrounding land-covers, the extent of the study areas influences the LSA, NDVI, and LST results.

Another limitation involves the 2010 end date of the systematically classified LULC data for the Phoenix metropolitan area. High resolution Google Earth imagery shows that land changes between 2010 and 2015 are minimal at the New River site. The Rio Salado site, however, continues to be developed, including large, commercial, and residential buildings along the eastern portions of Tempe Town Lake. This development would not likely change the composition trajectories identified from the 1985-2010 data, but it may have an impact on the configuration results of our study.

Finally, the disparate and disjointed means of measuring urban landscape composition and configuration is a limitation of this study and all LSA research. Many of the most commonly employed landscape metrics were developed for traditional ecological questions, and it is not clear how robust they may be for heterogeneous urban contexts. Inconsistencies may emerge in urban landscapes because the patterns and processes of urban areas differ from the non-urban settings. As an example, the urban heat island effect is a local climatological process unique to urban areas (Oke et al., 2017), and changing the metrics applied to LSA and temperature have yielded different outcomes (Li et al., 2016; Zhou et al., 2017, 2011). The research community has yet to systematically address this issue.

6. Conclusion

Our research investigated how the divergent design intentions of the Rio Salado and New River sites affected the areas' LSA and explored some environmental outcomes of this change. The findings indicate that few LSA changes were sufficiently unique to contribute to divergent environmental outcomes, but those that did had an outsized role in shaping the differences between sites. The design goals of the Rio Salado resulted in the interspersion of built-up, vegetation, and desert patches. Distribution (the interspersion of patches) was found to be statistically significant in terms of all analyzed environmental outcomes. The distribution of non-built (vegetation, water, and soil/desert) land cover was related to the Rio Salado bird community, and greater interspersion was related to cooler land surface temperature and higher vegetation presence/health at the Rio Salado site. The channelization of the Rio Salado into Tempe Town Lake allowed the site to support more waterbird and warbler species. In contrast, with less surface water and greater built-up area, the New River site supported mostly terrestrial species.

Advancing understanding about the relationship between LSA and environmental outcomes is important for a range of research fields—landscape and urban ecology, landscape architecture, urban climatology, geodesign, and LSS—and to urban planning. Many cities are developing or redeveloping their urban structure, especially in riparian areas. The composition and configuration changes cities make in these waterfront development projects will affect the areas' environmental outcomes. We encourage using (and improving) LSA's quantitative geospatial methods to plan land-cover change contextualized by the surrounding landscape as well as environmental, social, and economic goals. Our queries and findings are the beginning of a line of research that will provide insights on design goals and their impacts on composition, configuration, and environmental outcomes.

CRediT authorship contribution statement

Michelle Stuhlmacher: Conceptualization, Methodology, Formal analysis, Writing - original draft, Visualization, Funding acquisition. **Riley Andrade:** Conceptualization, Methodology, Formal analysis, Visualization. **B.L. Turner II:** Conceptualization, Writing - review & editing, Resources. **Amy Frazier:** Conceptualization, Methodology, Writing - review & editing. **Wenwen Li:** Data curation.

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Appendix A. Summary statistics for the Shape Index (SHAPE) and Euclidean Nearest-Neighbor Distance (ENN), the metrics for which there are patch level distribution values

Table A1
Summary statistics for the Shape Index (SHAPE) patch values at the Rio Salado site for all classes and all years. Crop values in 2010 are NA because there was no crop land cover that years.

	Class	Mean	Area Weighted Mean	Median	Range	Standard Deviation	Coefficient of Variation
1985	water	1.29	1.55	1.07	1.20	0.39	29.94
	built-up	1.43	6.13	1.00	6.10	1.11	77.85
	crop	1.28	1.33	1.21	0.67	0.21	16.60
	vegetation	1.15	1.48	1.00	1.21	0.23	20.23
	riverbed	1.23	4.55	1.00	4.33	0.60	49.00
1990	water	1.25	1.59	1.00	1.11	0.38	30.46
	built-up	1.35	7.26	1.00	6.78	1.01	74.67
	crop	1.11	1.18	1.00	0.50	0.16	14.30
	vegetation	1.16	1.94	1.00	1.58	0.29	24.68
	riverbed	1.20	3.45	1.00	3.17	0.54	44.69
1995	water	1.21	1.39	1.00	1.11	0.35	28.44
	built-up	1.25	9.04	1.00	8.26	1.13	89.98
	crop	1.02	1.04	1.00	0.25	0.07	7.03
	vegetation	1.17	1.89	1.00	1.53	0.31	26.75
	riverbed	1.24	3.31	1.00	2.97	0.54	43.18
2000	water	1.47	2.12	1.21	1.19	0.50	33.93
	built-up	1.28	5.61	1.00	4.79	0.78	61.19
	crop	1.04	1.05	1.00	0.25	0.09	8.45
	vegetation	1.18	2.11	1.00	1.78	0.31	26.66
	riverbed	1.21	3.45	1.00	3.78	0.55	45.48
2005	water	1.38	2.27	1.11	1.34	0.48	34.96
	built-up	1.41	9.28	1.00	8.38	1.58	112.38
	crop	1.06	1.15	1.00	0.25	0.11	10.19
	vegetation	1.17	2.12	1.00	2.27	0.33	28.00
	riverbed	1.24	2.72	1.00	2.90	0.49	39.61
2010	water	1.55	2.27	1.40	1.34	0.49	31.60
	built-up	1.27	8.65	1.00	7.70	1.17	92.44
	crop	NA	NA	NA	NA	NA	NA
	vegetation	1.18	1.98	1.00	1.97	0.33	28.07
	riverbed	1.30	2.49	1.00	2.85	0.51	39.29

Table A2
Summary statistics for the Shape Index (SHAPE) patch values at the New River site for all classes and all years

	Class	Mean	Area Weighted Mean	Median	Range	Standard Deviation	Coefficient of Variation
1985	water	1.70	2.80	1.31	1.94	0.79	46.47
	built-up	1.48	4.84	1.24	5.01	0.95	64.04
	crop	1.45	1.78	1.35	1.39	0.42	29.14
	vegetation	1.52	2.76	1.13	2.13	0.76	50.00
	riverbed	1.36	3.80	1.13	3.37	0.63	46.17
1990	water	1.35	2.71	1.13	2.14	0.68	50.82
	built-up	1.63	3.98	1.45	3.88	0.88	53.74
	crop	1.50	1.89	1.36	1.36	0.46	30.43
	vegetation	1.41	2.88	1.00	2.19	0.69	49.08
	riverbed	1.29	6.13	1.00	5.79	0.76	58.98
1995	water	1.46	3.07	1.00	2.47	0.80	55.19
	built-up	1.48	5.41	1.14	5.30	1.00	67.33
	crop	1.54	1.75	1.50	1.10	0.37	24.06
	vegetation	1.30	2.47	1.00	2.15	0.53	40.89
	riverbed	1.27	5.21	1.00	5.11	0.65	51.02
2000	water	2.09	3.61	1.29	2.73	1.25	59.86
	built-up	1.69	4.37	1.25	3.98	1.02	60.67
	crop	1.45	1.63	1.30	0.70	0.26	17.95
	vegetation	1.25	2.84	1.00	2.47	0.59	46.77
	riverbed	1.25	5.44	1.00	4.98	0.71	56.61
2005	water	1.45	3.48	1.19	2.94	0.85	58.69
	built-up	1.58	7.50	1.00	6.54	1.61	101.62
	crop	1.40	1.44	1.35	0.44	0.16	11.60
	vegetation	1.23	2.40	1.00	2.45	0.45	36.88
	riverbed	1.28	3.48	1.00	3.22	0.53	41.69
2010	water	1.49	2.91	1.19	2.27	0.80	54.02
	built-up	1.71	7.48	1.08	6.51	1.76	102.71
	crop	1.20	1.20	1.20	0.00	0.00	0.00
	vegetation	1.31	2.51	1.00	2.59	0.53	40.51
	riverbed	1.28	2.77	1.00	2.41	0.50	38.92

Table A3
Summary statistics for the Euclidean Nearest-Neighbor Distance (ENN) at the Rio Salado site for all classes and all years.

	Class	Mean	Area Weighted Mean	Median	Range	Standard Deviation	Coefficient of Variation
1985	water	209.53	142.44	161.67	480.83	150.41	71.78
	built-up	100.33	62.67	67.08	210.00	56.85	56.66
	crop	774.26	896.76	780.00	1221.46	467.89	60.43
	vegetation	187.95	178.89	120.00	1371.22	220.56	117.35
	riverbed	80.20	61.55	67.08	540.75	56.09	69.94
1990	water	102.10	112.41	60.00	168.47	68.38	66.97
	built-up	93.28	60.71	67.08	241.50	61.33	65.75
	crop	173.64	213.23	108.17	327.51	122.99	70.84
	vegetation	138.32	92.35	94.87	665.60	114.55	82.81
	riverbed	92.48	63.74	75.97	306.20	50.89	55.03
1995	water	357.23	386.89	231.86	648.03	273.38	76.53
	built-up	92.35	60.62	67.08	340.25	62.46	67.63
	crop	634.47	462.70	67.08	3723.45	1215.07	191.51
	vegetation	127.49	84.00	94.87	517.06	89.66	70.32
	riverbed	103.20	64.09	67.08	453.52	73.63	71.34
2000	water	365.19	463.73	300.00	635.06	220.37	60.34
	built-up	83.50	61.52	67.08	180.00	33.07	39.61
	crop	627.99	278.73	108.17	3789.60	1315.59	209.49
	vegetation	149.27	121.90	94.87	531.69	122.61	82.14
	riverbed	110.33	63.47	87.43	513.15	73.60	66.71
2005	water	187.40	109.27	115.93	420.88	137.74	73.50
	built-up	76.54	60.23	60.00	114.93	24.65	32.20
	crop	1726.85	2365.29	1344.72	1874.90	774.88	44.87
	vegetation	136.63	105.08	108.17	490.73	81.97	60.00
	riverbed	110.99	65.01	67.08	575.69	95.69	86.22
2010	water	198.53	93.76	94.87	330.00	128.00	64.47
	built-up	105.17	60.37	87.43	356.77	64.12	60.97
	crop	NA	NA	NA	NA	NA	NA
	vegetation	154.41	107.50	120.00	661.25	118.07	76.46
	riverbed	105.82	67.42	90.00	366.38	63.16	59.69

Table A4
Summary statistics for the Euclidean Nearest-Neighbor Distance (ENN) at the New River site for all classes and all years.

	Class	Mean	Area Weighted Mean	Median	Range	Standard Deviation	Coefficient of Variation
1985	water	113.63	118.23	113.63	11.79	5.89	5.19
	built-up	127.79	74.53	89.64	314.64	80.86	63.28
	crop	137.12	86.72	63.29	481.39	134.62	98.18
	vegetation	323.58	90.97	203.42	1233.39	319.34	98.69
	riverbed	100.47	63.68	66.81	329.83	68.15	67.83
1990	water	419.66	198.83	300.66	1159.97	381.62	90.94
	built-up	112.60	80.01	89.64	314.64	67.13	59.62
	crop	119.29	144.90	59.76	488.76	112.47	94.29
	vegetation	416.61	179.26	311.96	1392.11	393.93	94.55
	riverbed	104.93	65.52	66.81	395.36	72.31	68.91
1995	water	148.05	90.93	89.64	471.29	144.70	97.74
	built-up	98.59	66.85	84.51	263.44	63.85	64.76
	crop	171.29	78.68	87.27	795.87	232.48	135.73
	vegetation	225.42	127.82	160.91	597.60	185.57	82.32
	riverbed	131.54	76.90	94.49	448.20	93.74	71.26
2000	water	604.29	1463.32	107.73	1489.66	702.23	116.21
	built-up	76.67	63.02	66.81	67.01	22.07	28.79
	crop	558.94	164.82	84.51	2423.16	962.16	172.14
	vegetation	247.12	157.44	119.52	762.35	218.24	88.31
	riverbed	156.86	71.22	149.40	426.65	94.59	60.30
2005	water	342.04	113.20	107.73	734.95	323.57	94.60
	built-up	70.09	59.81	59.76	67.01	18.03	25.72
	crop	629.04	350.99	123.20	2273.87	888.30	141.21
	vegetation	156.89	160.72	119.52	533.34	113.82	72.55
	riverbed	136.93	72.25	89.64	870.85	142.78	104.27
2010	water	590.72	97.36	107.73	3030.04	1117.87	189.24
	built-up	65.06	59.78	59.76	24.75	9.07	13.94
	crop	NA	NA	NA	NA	NA	NA
	vegetation	156.53	130.71	107.73	418.32	116.71	74.56
	riverbed	97.64	73.06	66.81	236.04	55.11	56.44

Appendix B. Common name, scientific name, and 4-letter alpha code for all bird species in our analysis

Table A5
Common name, scientific name, and 4-letter alpha code for all bird species in our analysis. The 4-letter alpha codes are the ones used during the CAP LTER data collection—English name 54th AOU Supplement (2013) alpha codes.

4-letter alpha code	Common Name	Scientific Name
ABTO	Abert's Towhee	*Melozone aberti*
AMBI	American Bittern	*Botaurus lentiginosus*
AMCO	American Coot	*Fulica americana*
AMKE	American Kestrel	*Falco sparverius*
ANHU	Anna's Hummingbird	*Calypte anna*
ATFL	Ash-throated Flycatcher	*Myiarchus cinerascens*
AUWA	Audubon's Warbler	*Setophaga coronata auduboni*
BCNH	Black-crowned Night-Heron	*Nycticorax nycticorax*
BEKI	Belted Kingfisher	*Megaceryle alcyon*
BEWR	Bewick's Wren	*Thryomanes bewickii*
BGGN	Blue-gray Gnatcatcher	*Polioptila caerulea*
BHCO	Brown-headed Cowbird	*Molothrus ater*
BLPH	Black Phoebe	*Sayornis nigricans*
BNST	Black-necked Stilt	*Himantopus mexicanus*
BRSP	Brewer's Sparrow	*Spizella breweri*
BTGN	Black-tailed Gnatcatcher	*Polioptila melanura*
BTYW	Black-throated Gray Warbler	*Setophaga nigrescens*
CACW	Cactus Wren	*Campylorhynchus brunneicapillus*
CANG	Canada Goose	*Branta canadensis*
CHSP	Chipping Sparrow	*Spizella passerina*
CITE	Cinnamon Teal	*Spatula cyanoptera*
CLSW	Cliff Swallow	*Petrochelidon pyrrhonota*
COGA	Common gallinule	*Gallinula galeata*
COHU	Costa's Hummingbird	*Calypte costae*
CORA	Common Raven	*Corvus corax*
COYE	Common Yellowthroat	*Geothlypis trichas*
EUCD	Eurasian Collared-Dove	*Streptopelia decaocto*
EUST	European Starling	*Sturnus vulgaris*
GAQU	Gambel's Quail	*Callipepla gambelii*
GBHE	Great Blue Heron	*Ardea herodias*
GIWO	Gila Woodpecker	*Melanerpes uropygialis*
GREG	Great Egret	*Ardea alba*
GRHE	Green Heron	*Butorides virescens*
GRYE	Greater Yellowlegs	*Tringa melanoleuca*
GTGR	Great-tailed Grackle	*Quiscalus mexicanus*
GTTO	Green-tailed Towhee	*Pipilo chlorurus*
HOFI	House Finch	*Haemorhous mexicanus*
HOSP	House Sparrow	*Passer domesticus*
HOWR	House Wren	*Troglodytes aedon*
INDO	Inca Dove	*Columbina inca*
KILL	Killdeer	*Charadrius vociferus*
LBDO	Long-billed Dowitcher	*Limnodromus scolopaceus*
LBWO	Ladder-backed Woodpecker	*Dryobates scalaris*
LEGO	Lesser Goldfinch	*Spinus psaltria*
LESA	Least Sandpiper	*Calidris minutilla*
LISP	Lincoln's Sparrow	*Melospiza lincolnii*
LUWA	Lucy's Warbler	*Leiothlypis luciae*
MALL	Mallard	*Anas platyrhynchos*
MAWR	Marsh Wren	*Cistothorus palustris*
MGWA	MacGillivray's Warbler	*Geothlypis tolmiei*
MODO	Mourning Dove	*Zenaida macroura*
NECO	Neotropic Cormorant	*Phalacrocorax brasilianus*
NOCA	Northern Cardinal	*Cardinalis cardinalis*
NOFL	Northern Flicker	*Colaptes auratus*
NOMO	Northern Mockingbird	*Mimus polyglottos*
NRWS	Northern Rough-winged Swallow	*Stelgidopteryx serripennis*
OCWA	Orange-crowned Warbler	*Leiothlypis celata*
OSPR	Osprey	*Pandion haliaetus*
PBGR	Pied-billed Grebe	*Podilymbus podiceps*
PHAI	Phainopepla	*Phainopepla nitens*
PWWR	Pacific/Winter Wren	*Troglodytes pacificus/ Troglodytes hiemalis*

(*continued on next page*)

Table A5 (*continued*)

4-letter alpha code	Common Name	Scientific Name
PYRR	Pyrrhuloxia	*Cardinalis sinuatus*
RCKI	Ruby-crowned Kinglet	*Regulus calendula*
ROPI	Rock Pigeon	*Columba livia*
RWBL	Red-winged Blackbird	*Agelaius phoeniceus*
SAPH	Say's Phoebe	*Sayornis saya*
SOSP	Song Sparrow	*Melospiza melodia*
SPSA	Spotted Sandpiper	*Actitis macularius*
TOWA	Townsend's Warbler	*Setophaga townsendi*
VERD	Verdin	*Auriparus flaviceps*
VIRA	Virginia Rail	*Rallus limicola*
WCSP	White-crowned Sparrow	*Zonotrichia leucophrys*
WEKI	Western Kingbird	*Tyrannus verticalis*
WEME	Western Meadowlark	*Sturnella neglecta*
WESA	Western Sandpiper	*Calidris mauri*
WETA	Western Tanager	*Piranga ludoviciana*
WISN	Wilson's Snipe	*Gallinago delicata*
WIWA	Wilson's Warbler	*Cardellina pusilla*
WWDO	White-winged Dove	*Zenaida asiatica*
YEWA	Yellow Warbler	*Setophaga petechia*
YRWA	Yellow-rumped Warbler	*Setophaga coronata*

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