Designing a Multifunctional Urban Open Space Network Across the Phoenix Metro

Applied Project

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Abstract
Urban areas are dominated by the built environment, and any remaining open spaces, vegetated and riparian areas that provide valuable social and ecological functions are increasingly fragmented and threatened by sprawling urban growth. Connecting these remnant open spaces with multifunctional corridors can help to enrich and conserve biodiversity, while providing various ecosystem services. Researchers, planners, and other decision-makers have applied landscape ecology principles to strategically plan open space networks. This project develops a model for identifying and prioritizing potential corridors based on social and ecological criteria and applies it to the Phoenix Metropolitan area, which is one of the fastest growing regions in the United States. Different land uses and social and ecological criteria are prioritized based on a survey of local planning experts. Survey results are used to develop a geospatial (GIS) model, which identifies the optimal 'least-cost' paths between existing parks, for example routes through existing canal paths and vacant land, as well as ecologically sensitive and hotter areas of the city. These analyses can inform the regional open spaces vision and individual community's future land use planning. Moreover, the general modeling approach can be used by other communities that seek to develop their own multifunctional open space networks.

1) Introduction / Study Area

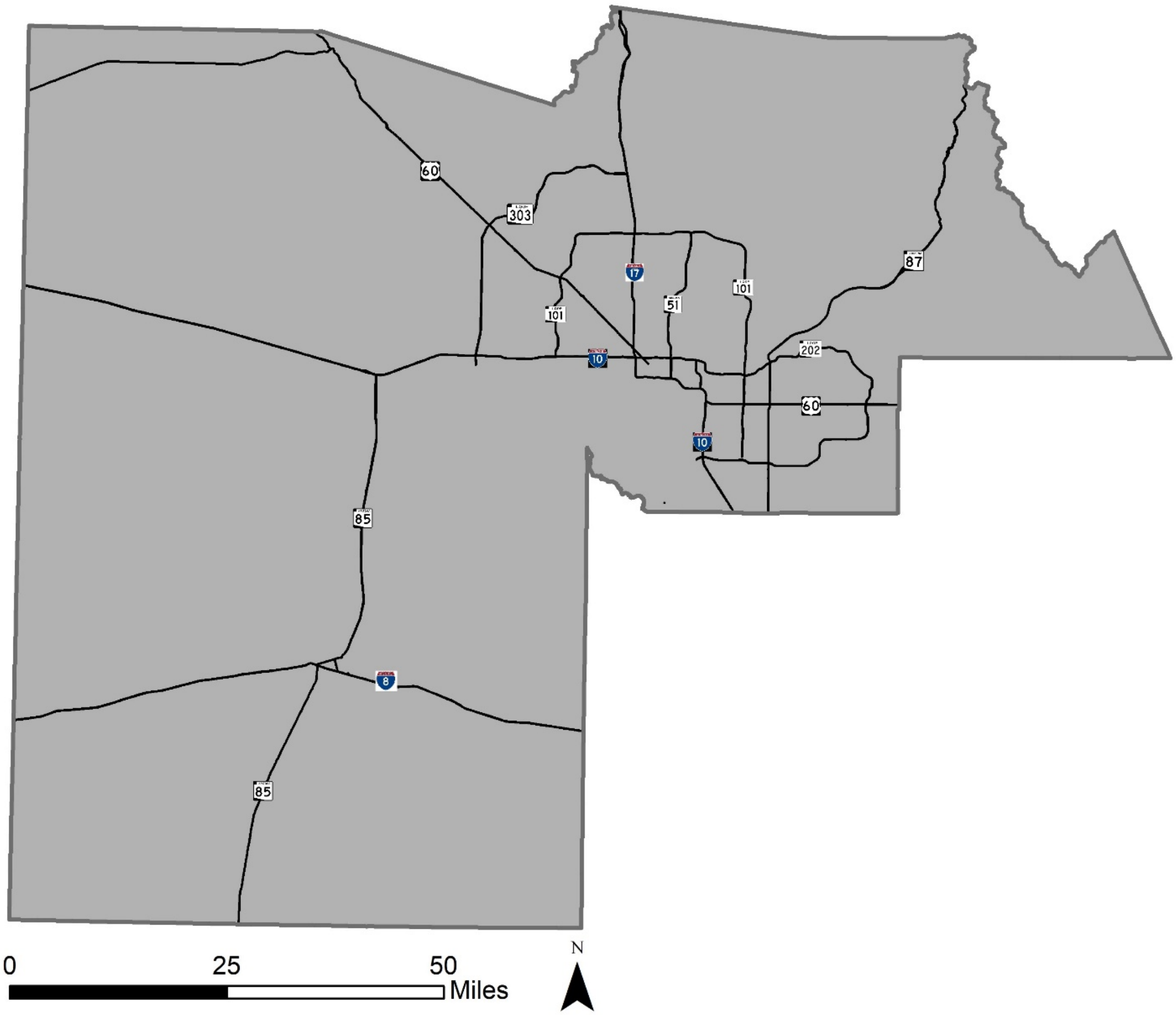

Figure 1. 1 Maricopa County

Maricopa County is located in central Arizona, and from 2016 to 2017 it was the fastest growing county in the nation (US Census 2016). In the face of rapid growth, some collaborative efforts are underway to conserve and restore natural areas, increase connectivity and mobility, and expand the region's recreation opportunities. However, the scope of the challenge is great. Over the last 50 years, the Phoenix metro has sprawled decision-making regarding open space in this nearly six-million-acre county across more than 20 cities and towns, three tribal nations, and a plethora of land ownership types and management agencies. Data needed to support regional decisions is scattered across organizations, institutions, agencies, and individual researchers. This complexity in decision-making and the acquisition of data to support decisions severely complicates the region's ability to maximize the full range of social, ecological, and economic benefits delivered by open space.

Social and ecological open spaces in the Phoenix metro have been diminished as a result of urban growth and will likely continue to shrink as the urban footprint sprawls and fragments across the landscape. Urbanization in Maricopa County, specifically the Phoenix metro, has occurred rapidly over the last few decades, with the population doubling twice in the last 35 years (Central Arizona - Phoenix LTER, n.d.). The population is projected to reach between seven and eight million by 2030 (Berling-Wolff & Wu, 2004). Worldwide, urbanization is one of the main causes of habitat fragmentation and biodiversity loss because it alters the landscape's ecological functions and processes (Alberti, 2005; Forman, 1995). Fragmentation is a process that leads to isolated patches of habitat that ultimately reduce the total core habitat area and increase edge effects around habitat patches. Edge effect areas are most altered and affected by external perturbations such as natural disasters, seasons, and invasion of other species (Laurance et al., 2007). As species leave the main core habitat areas, mortality rates increase (Fahrig, 2002). Moreover, as connectivity of patches is lost causing species to be isolated from other patches, which can ultimately lead to extinction.

In addition to habitat fragmentation and associated ecological challenges, urbanization, and different aspects of the built environment can have other negative consequences on the environment, including localized climate changes through the urban heat island effect as well as air and water pollution (Jenerette et al., 2007; Pickett et al., 2001). One strategy to mitigate some of these impacts is to preserve and connect open spaces, such as parks, preserves, trails, wilderness areas. Such green networks can provide many ecological benefits, including enhanced biodiversity and local climate regulation (Davies et al., 2015). While preserving patches of open space is valuable, their value and ecological resilience is increased if these are connected (Shinderman, 2015). These networks also serve a valuable social function, providing people with spaces to recreate and interact with nature, and ultimately improving physical and mental health. One study shows that urban parks and other vegetated areas can help reduce people's stress levels and improve physical health while also increasing social cohesion among residents (Annerstedt, Konijnendijk, Busse Nielsen, & Maruthaveeran, 2013). Another study shows that having more access to residential green spaces reduces rates of depression (Cohen-Cline, Turkheimer, & Duncan, n.d.).

The Central Arizona Conservation Alliance (CAZCA) is working to resolve these issues at the regional scale, both by co-creating a unified Regional Open Space Strategy for Maricopa County and developing a GIS-based decision support tool called a "Green Print." Funded by the Trust for Public Land, The Nature Conservancy, and CAZCA, the tool compiles and weights data from across agencies and organizations to identify areas of high biological value for conservation (e.g. for habitat integrity, water resources, etc.). Most of these larger priority areas are on the fringes of the city, but there are also important sites to preserve and connect within the more urbanized parts of city that would provide multiple recreation, environmental, and mobility benefits to urban residents and wildlife.

This project focuses on identifying these finer-scale opportunity areas throughout Phoenix and its suburbs, using geospatial (GIS) analysis to identify important current and future open spaces and optimal paths for linking them to enhance social and ecological connectivity. The model developed identifies the most feasible routes between these parks and open spaces, such as along canals or over vacant or public land. Another model adds additional social criteria, prioritizing areas without sufficient park access and hotter parts of the city. These routes could potentially be developed into greenways as cities see fit.

This applied project draws on theories and research on landscape ecology and ecological design that show that connectivity between open spaces is beneficial to humans and biodiversity, which motivates the following research question: what is the optimal open space network based on both social and ecological criteria for the Phoenix Metro? The results of this project can help inform planners, regional planners, designers, and other decision makers in identifying opportunities to build a robust open space network in the Phoenix metro.

The next section provides a review of relevant literature on green infrastructure/open spaces, best practices for planning green infrastructure networks and involving different stakeholders. Section 3 outlines the methodology and data used in this project, with the results presented and discussed in Section 4.

1) Theoretical Framework

Fragmentation (from city development, industrialization, city sprawl, and increased agriculture) and its effects on natural habitat is a major threat to biodiversity. It causes a geographical separation of species and a reduction in core habitat, often eventually leading to the loss of native species (Ferretti & Pomarico, 2013; Marzluff, 2001). For the past few decades, awareness of fragmentation effects has ignited organizations' and cities' desire to create plans to best mitigate and reduce excessive urbanization. Proposed plans usually identify potential connections between existing habitat patches, and thus the creation of ecological corridors.

An ecological corridor is an area that allows for species' movement (Ongman, Jongman, & Pungetti, 2004). These corridor networks are made up of two elements, one being hubs, which are core areas with high ecological value, and the second being links, which are the corridors or the connections between those hubs (Ferretti & Pomarico, 2013).

In earlier studies, patch connectivity was used to identify habitat connections. This method looks at the shortest Euclidian distance between each of the patches and their nearest neighbor without taking into consideration the land covers between patches (Moilanen & Hanski, 2001). However, more recently research has focused on using 'least-cost' modeling to find more functional linkages between habitat (Alexander, Olimb, Bly, & Restani, 2016; Pirnat & Hladnik, 2016; Porter, Dueser, & Moncrief, 2015; Schadt et al., 2002; Wang, Savage, & Bradley Shaffer, 2009). This modeling tool originates from graph theory, which refers to a set of vertices (points or locations) and edges (lines or corridors) that connect each of the locations to each other (Carlson, n.d.).

In the ‘least-cost’ model each cell is assigned a cost or a resistance value, this value is used to then calculate connectivity between the source location and the surrounding desired locations, by adding each cell value to a total cost. The model takes into consideration the positive (habitat, or low-cost cells) and negatives (barriers, high-cost cells) that each cell location has. GIS modeling makes these calculations more efficient, allowing researchers to find optimal connections between core ecological areas.

Malczewski (1999) argues that combining GIS with multicriteria analysis (MCA) is an effective way to model potential ecological connections. GIS tools can be used to maintain, store, and visualize data, while MCA brings other techniques and algorithms for structuring decision-making about the relative importance of different criteria and how to combine them (Geneletti, 2009). MCA also supports the comparison of alternatives through stakeholder participation in the decision-making process (Ferretti & Pomarico, 2013).

Most open space network studies focus on ecological variable and connectivity, yet these networks may also have important social benefits. Focusing on creating multifunctional networks of open spaces may broaden support for their development beyond those concerned with conservation. Indeed, work on greenways in the last few decades has shifted from only focusing on conserving open space for species habitat to combining this with recreational activities (Lindsey, 2003).

Research has shown that open spaces provide various benefits to nearby areas. Depending on the area size and the wind direction, as well as vegetation, open spaces can cause a cooling effect to the area (Dimoudi & Nikolopoulou, n.d.). Research also shows that open spaces with scattered trees also support a larger biodiversity (Prevedello, Almeida-Gomes, Lindenmayer, & Jayme Prevedello, 2018). It is also important for residents to have easy access to these open spaces, because of their cooling effect and because of their effects on mental health. A few studies have shown that green open space has a positive effect on mental health (lower levels of anxiety and better moods) (de Vries, Verheij, Groenewegen, & Spreeuwenberg, 2003; Nutsford, Pearson, & Kingham, 2013). Another study shows that green inequities are affecting resident’s health. Urban residents with little access to green vegetation tend to also live in communities with poor health and unsafe areas, the poor health could be potentially mitigated if more green vegetation were accessible (Wolch, Byrne, & Newell, 2014). Other research suggests that when disadvantaged populations have exposure to urban vegetation it may have a greater impact on physical health than other places (Mitchell & Popham, 2008). Access to green space and vegetation for residents should be improved in cities if they wish to improve the mental and physical health of their populations.

Nevertheless, few studies to date have focused on developing green network planning models that incorporate both social and ecological criteria, especially in the Phoenix metropolitan area. In this paper, we will use the application of least-cost modelling based on the spatial analyst tool ‘cost-distance’ extension of ArcView combined with multicriteria analysis based on a local stakeholder survey (ESRI 1996). We will apply this method to identify potential multifunctional corridors that would connect existing open spaces in Phoenix, providing social and ecological benefits.

2) Data and Methods

The project applies the latest methods in geospatial (GIS) modeling to create a decision support tool. First, various GIS datasets were assembled (land-use, landscape ecology, land cover data and priority areas to connect) and ground-truthed to supplement the existing data in the Green Print. Next we sent a survey to a wide range of local and regional planning experts to 1) prioritize the conservation areas or parks to be connected and 2) assign 'weights' to different land-uses for the optimal path analysis based on the perceived cost and desirability of converting them into multifunctional greenways. Survey results were aggregated and then used to develop an optimization model, which calculates the shortest, 'least-cost' paths. The resulting paths were analyzed and documented through this written report and maps.

Data

The data used came from a few different sources. The land-use dataset is created and managed by the Maricopa Association of Governments (MAG); this data contains all the necessary metadata to effectively understand each parcel's land-use. For example, the data will show, as of 2016, if the land is vacant, commercial, residential, or industrial, or open space. MAG also owns layers for their public parks and existing trails. The heat layer identifies hotspots across the region and consists of high resolution near-surface air temperature aggregated to the block group level. The data is a 10-year average (2008-2017) with days of highest temperature exceeding 105F. Relatively park poor areas are identified using standard criteria (1/2-mile or 10-minute walk service areas around existing city parks). The ecological data, species richness and riparian areas come from CAZCA and The Trust for Public Land (TPL), which can be seen on their GreenPrint GIS portal. The species richness data is a count of species within the study area, while the riparian layer contains plant communities contiguous to and affected by surface and subsurface hydrologic feature water bodies (rivers, streams, lakes, or drainage ways. For more detailed information on data used review the criteria and descriptions table in the Appendix.

Identifying key habitat patches to connect

In urban areas parks often represent some of the most important remnant habitat patches, as well as important locations for social recreation and interaction with nature. Previous corridor modeling studies have used parks to represent habitat patches for connection (Zhang, Meerow, Newell, & Lindquist, 2019). Phoenix has a number of large parks, including the nation's largest municipal park (South Mountain). We identified 203 parks at 30 acres or larger to model connections between each of them, but soon realized that the model would run for a few weeks, making it impossible to meet study deadlines. We then decided to use the top 20 largest parks located throughout the study boundary. These 20 parks are shown in Figure 3.1. Open spaces were identified through a definition query to find the desired parks to connect. The selected park parcels (largest 20 parks) were then changed from polygon to point layer. Each park is represented as a point located at the centroid of each park, which can be imputed into the model connecting each origin to a destination.

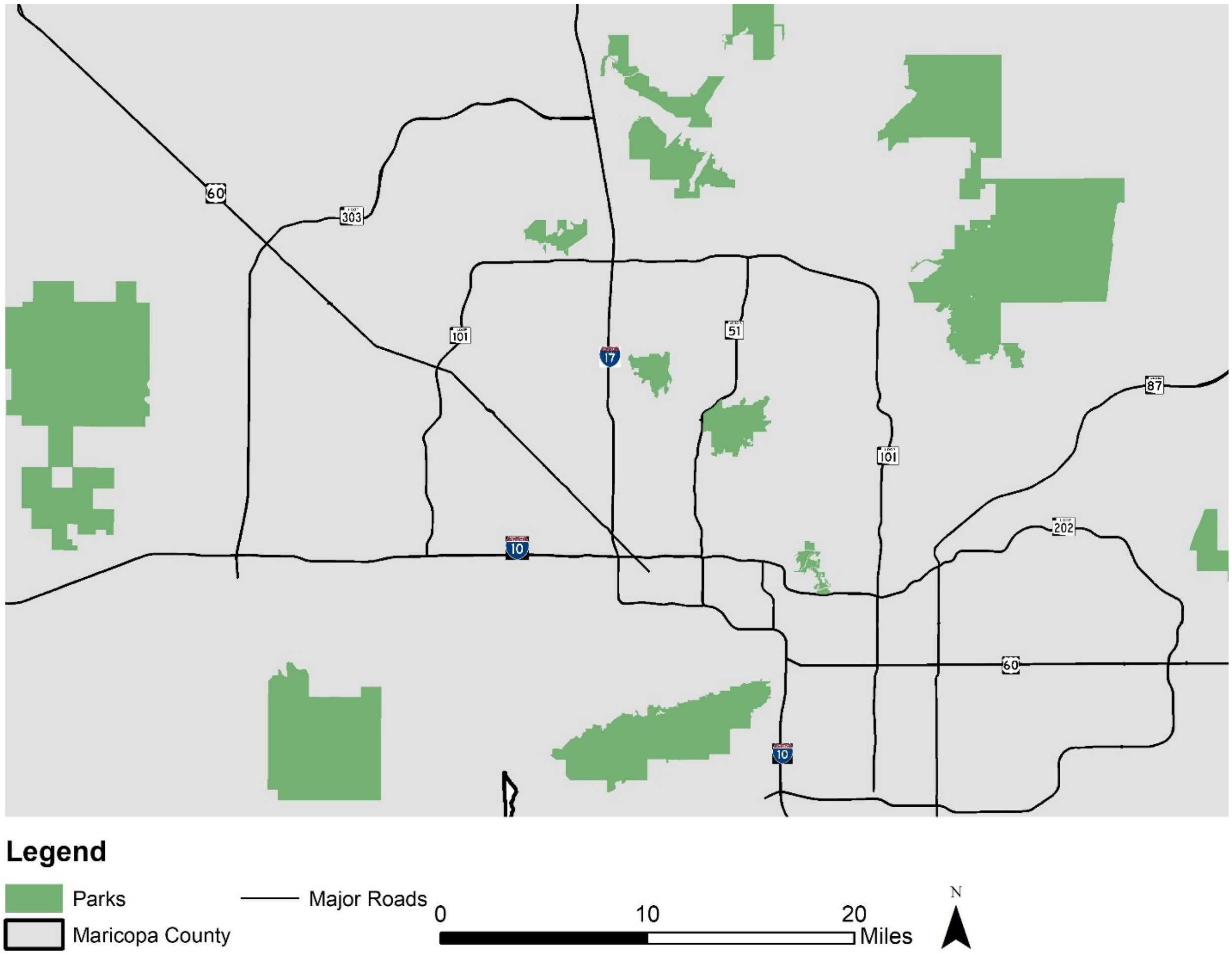

Figure 3. 1 Open Spaces

Finding connections between parks using the least-cost algorithm

We use a least-cost path approach to identify the most feasible routes for connecting the selected 20 parks. Previous studies used the least-cost algorithm to calculate the cheapest and shortest distances to connect habitat patches (Adriaensen et al., 2003; Avon & Bergès, 2016). This tool has also been used to determine habitat restoration in fragmented areas (Porter et al., 2015). This project uses the same approach to identify potential connections between parks and open spaces in the urbanized Phoenix metro. The least-cost algorithm is a simple method for identifying the least 'costly' path from one location to another. 'Cost' can refer to the actual estimated cost of developing through that area, or more often, it is an estimate of the perceived difficulty associated with moving through that particular location based on the current land use. The source layer divides into pixels with a number (cost) assigned to each. The path calculates from its starting point by first looking at each cell surrounding it and determining which next pixel will give the path the overall least-cost as it progresses towards the ending location. This model is based on an eight-neighbor-pixel algorithm that allows for the path to move in horizontal, vertical, and diagonal directions. The cumulative cost calculation for moving horizontally or vertically is the cost to reach the source pixel plus the average cost to move from the first pixel and the second pixel. The summation of this calculation = $\frac{Pixel\ 1\ Cost+Pixel\ 2\ Cost}{2}$ + $\frac{Pixel\ 2\ Cost+Pixel\ 3\ Cost}{2}$…, while if the direction of the path is diagonal the calculation is multiplied by the square root of the two pixels $1.4142\,\frac{(Pixel\ 1\ Cost+Pixel\ 2\ Cost)}{2}$.

The cost-distance analysis
The cost-distance analysis uses two layers. One of those layers is the source layer: in this case point layer of parks and open spaces (the priority areas to connect). The second layer is the resistance or friction layer (county land-use, ecological, and social data. See Appendix for all land-use, ecological, and social layers and their descriptions), which has costs associated to each. The cost layer identifies the perceived 'cost' of developing each pixel individually.

To create the cost raster, all the data needed to be in a similar classification for combining layers together. Each layer was reclassified to be on the same scale (1 to 10 by 1) using GIS. For example, if a land-use is ranked with a '1' then it will be the least costly way, while if a land-use is ranked with a '10' it is considered the most-costly. The two cost raster layers, what we call the multifunctional and feasibility layer, are both a 10 by 10-meter pixel array (73,276,800 pixels) of Maricopa County with a cost of a number between 1 and 10 assigned to each pixel.

Land-use data was changed from vector to raster data cells while assigning each land-use code a number between 1 and 10 by 1. The next step required changing the two ecological layers – representing species richness and riparian data – to the same classification scale, and then combining them into a single layer using the raster calculator tool. The tool takes each cell on both layers and matches them to add their cost together for the final ecological layer output. For example, if a cell had a 0 for riparian area and a 3 in species richness that cell in the output would be a 3. This same approach was used when creating the social layer. The social layer added pixels from an access to parks layer and a temperature layer together. Land-use, ecological, and social layer were then placed into the overlay tool with each of the three layers having an associated weight to it.

Identifying costs for land uses and planning priorities using an expert stakeholder survey
Following the social-ecological approach of (Zhang et al., 2019) our cost surface is based on existing land uses, ecological, and social data, and the perceived feasibility of developing that land into a corridor, with more feasible areas being rated lower cost and less feasible higher cost. In an effort to determine the most accurate costs taking into local constraints, we surveyed a diverse group of local experts rather than assigning costs from my own perspective. In addition to land-use costs the survey included information on an additional social layer and an ecological layer for experts to weight. Ultimately, the survey was created to figure out which land-uses and layers are most important and least costly. For example, the survey helps us to determine how many times more costly, or difficult it would be to develop a location with an existing building than vacant land. The cost for buildings is then applied to each of the cells with the attribute

buildings, while the cost for vacant parcels will be applied to those cells with vacant parcels. This collaborative effort produced a more realistic and credible feasibility layer for the model.

An 8-question online survey was created through Qualtrics containing a series of questions asking respondents about the feasibility and relative importance of different land-use layers for creating an open space network. A diverse set of local experts were asked to fill out the survey. The survey's responses were then aggregated and used in creating the cost surface for the least-cost path analysis. The entire survey can be seen in the appendix. The survey was first sent via email on February 7th to a list of 110 individuals. Of the original 110 emails sent, 8 bounced back suggesting an error or that those people had changed positions. Over the course of 4 weeks, 3 reminder emails were sent to those that may have forgotten to look through the survey. The final survey data showed that there were 52 people that went through the survey and of those 35 responded to the survey questions. 35 responses of 110 gives a 32 percent response rate. The 35 responses came from planners, directors of cities, professors, landscape architects, ecologists, and other professionals located throughout the metro region working for cities, Maricopa county, Desert Botanical Gardens, Arizona State University, and other organizations. Responses to question 6 of the survey is shown in Figure 3.2. Over 50 percent of respondents either work for the county or for non-profits in the region, while the remaining is split between cities, educational, private and other.

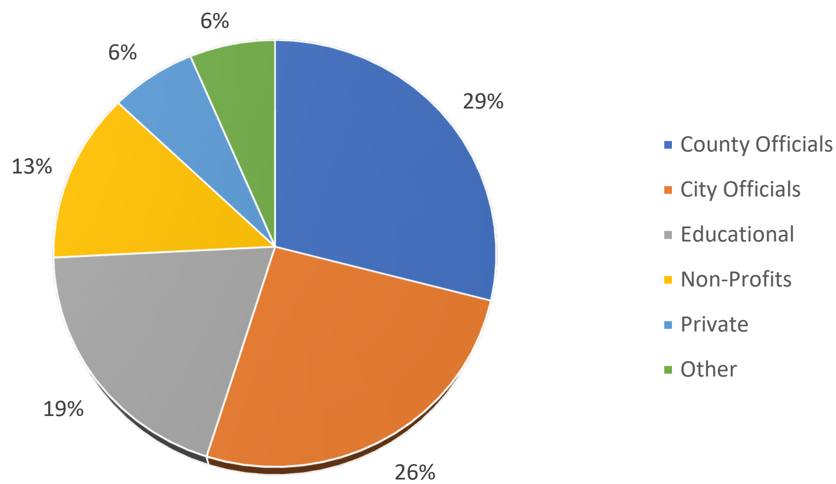

Figure 3. 2 Respondents Work Place

The land-use codes were condensed down to 14 rather than 30 to be used in the survey. Table 3.1 illustrates this and also contains the costs that were associated with them in the model. These costs came from regional experts that took the survey. Experts ranked each one of the land-uses (14 of them) on a scale of 1 to 10 with 1 being the least costly to develop. The results were then downloaded and averaged amongst all the surveys taken to give a final cost number. Trails and bike paths (cost of 2) and golf course (cost of 6) is interpreted as trails and bike paths being three times less costly then developing on through a golf course. The standard deviation shows that the some of the respondent's opinions were different from each other. For example, transportation has the largest standard deviation, 3.02; however, most respondents agreed that existing trails and bike paths were the least costly for the path to run through had the lowest standard deviation of .97.

Land-Use	Feasibility	Std. Deviation
Trails and Bike Paths	2	0.97
Open Space / Agriculture	3	2.30
Golf Course	6	2.76
Residential	7	2.79
Transportation	6	3.02
Developing Residential / Employment	7	2.44
Vacant Land	3	2.14
Commercial / Industrial / Office / Hotel / Resort / Airport / Mixed-use	8	2.37
Special Event/Military	7	2.58
Passive / Restricted Open Space / Undevelopable	3	1.89
Religious / Institutional	6	2.99
Educational	6	2.41
Medical / Nursing Facilities	8	2.54
Water Bodies	4	2.90

Table 3. 1 Land-Use

Modeling

The three layers were placed into the weighted overlay tool in ArcMap, which sets a weight to each layer, the higher weight has a larger pull when the path is traveling through each cell. The survey asked the experts to weight each of the three layers as a percentage from 1 to 100 with all three layers totaling to 100 percent. The averaged results from the survey were weighted at 39 percent, 34 percent, and 27 percent for land-use, ecological, and social layers respectively. After the source and resistance layers were created with the survey weights the model was run. The model was built in a python script as a loop because there are many different parks and open spaces to connect in the Phoenix metro. The least-cost path tool was used to identify the lowest cost routes, based on the weighted multifunctional layer. As the model runs it travels through a one cell wide path (10 by 10 meters) from a destination to another destination. Since there will be multiple parks that we will connect, we set the parameters of this tool to identify the lowest cost path between each park. The script ran for a little over 20 hours. The following figures illustrate the individual data that was implemented into the model.

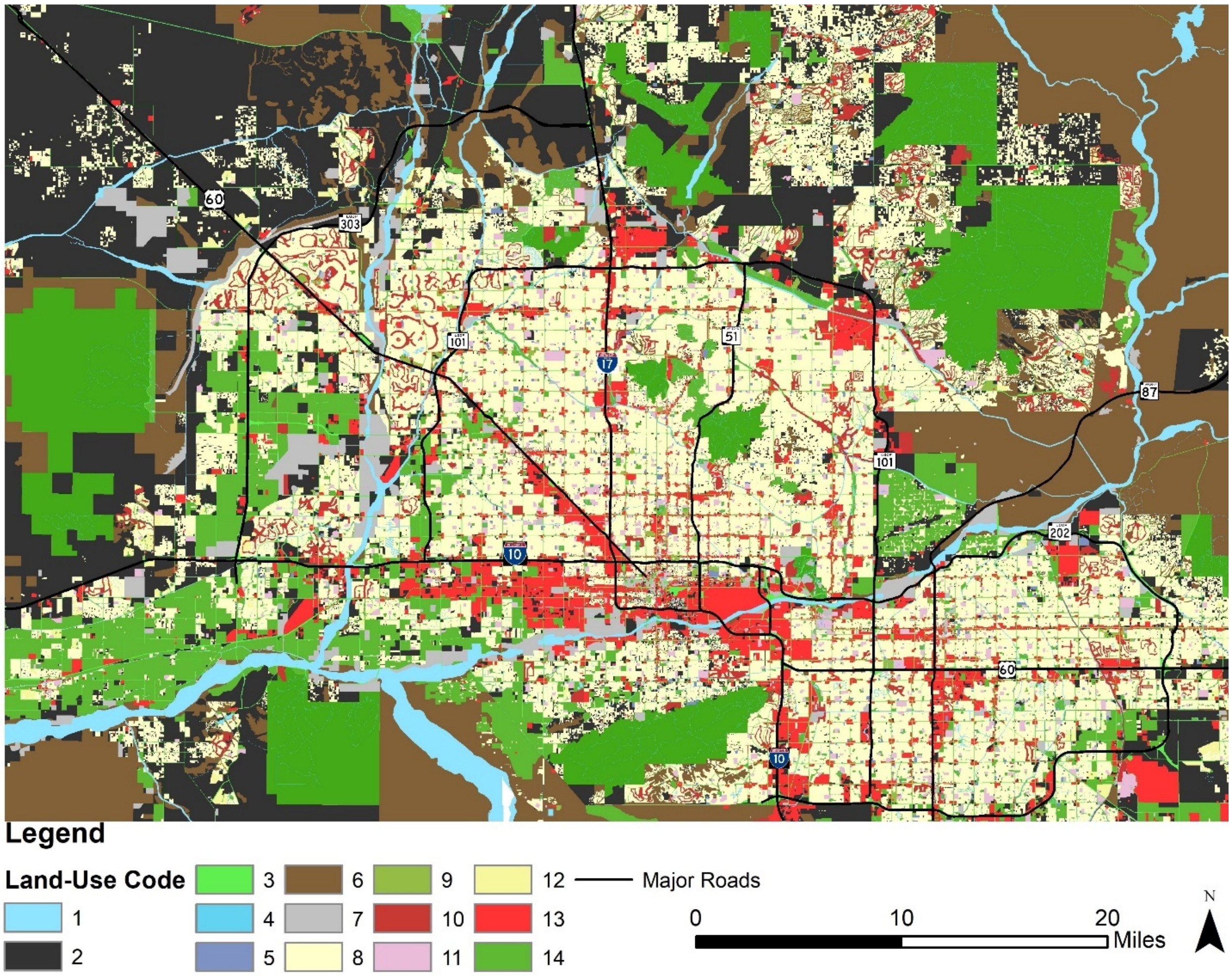

Figure 3. 3 Land-Use

Table 3.2 contains the land-use code descriptions from Figure 3.3 legend. This table is also used for Figure 4.5.

Land-Use Code	Description
1	Water Bodies
2	Vacant Land
3	Transportation
4	Trails and Bike Paths
5	Religious / Institutional
6	Passive / Restricted Open Space / Undevelopable
7	Special Event / Military
8	Residential
9	Medical / Nursing Facilities
10	Golf Course
11	Educational

12	Developing Residential / Employment
13	Commercial / Industrial / Office / Hotel / Resort / Airport / Mixed-Use
14	Open Space / Agriculture

Table 3. 2 Land-Use Legend

Figure 3.4 shows the temperature vulnerability for all census blocks in metro Phoenix. This number is calculated by taking the 10-year average days exceeding 105ºF from years 2007 – 2017 (Turner, Ritts, & Gregory, 2017). The data was then reclassified to raster format which is shown below in Figure 3.4. The northeast section of the figure has the least amount of days exceeding 105ºF, while the orange and red colors (colors covering most of the metro Phoenix) are above 56 averaged days. The residents that live in these areas experience the more extreme heat that comes to the region throughout the summer months.

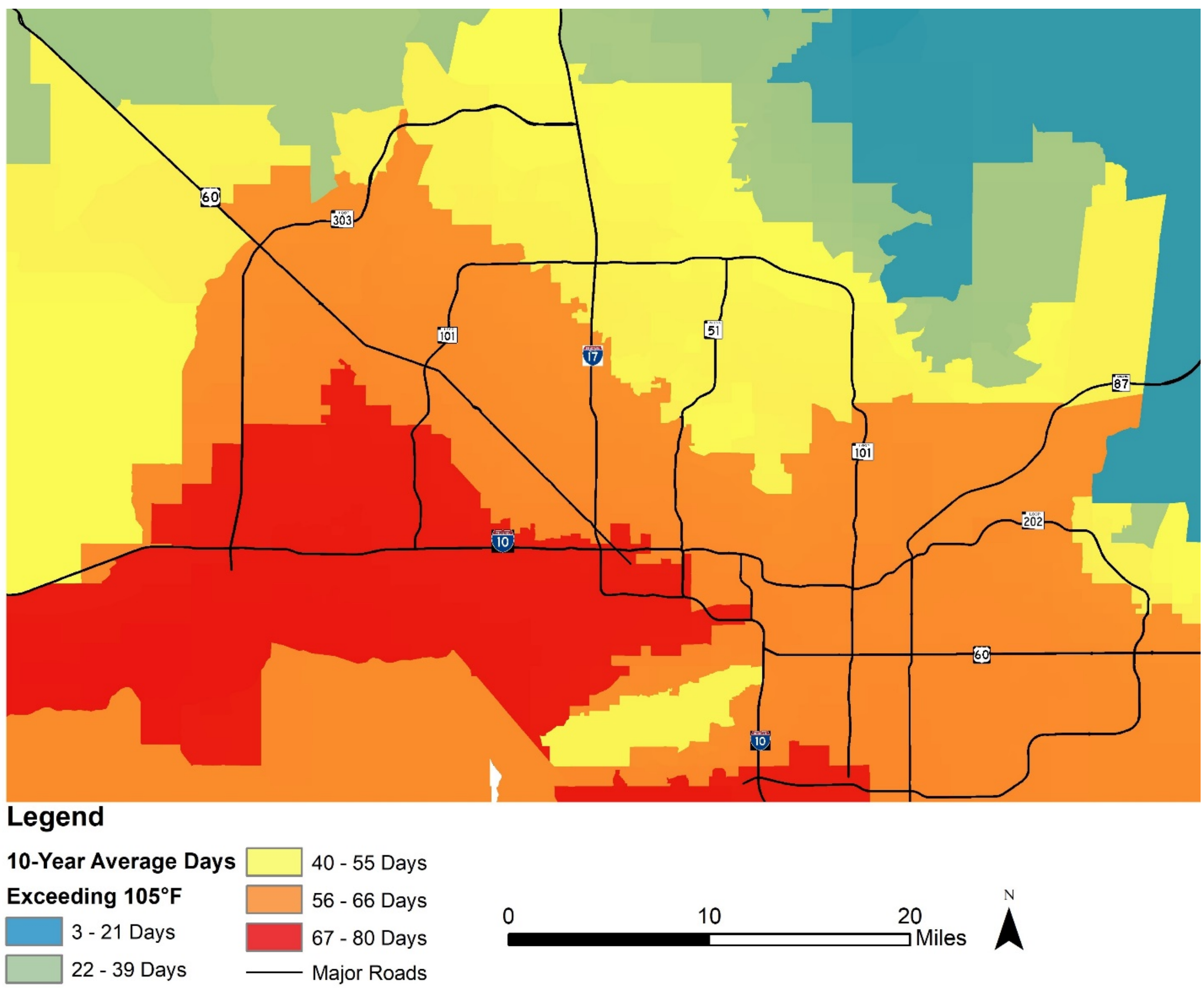

Figure 3. 4 Temperature Vulnerability

Figure 3.5 illustrates, at a small scale, ½ mile network walking distance to each of the park entrances. A ½ mile distance doesn't cover much of the region's population. The top largest 20 parks are mostly accessible through vehicle making it difficult for residents and visitors without a vehicle and those that that may have little time in their day.

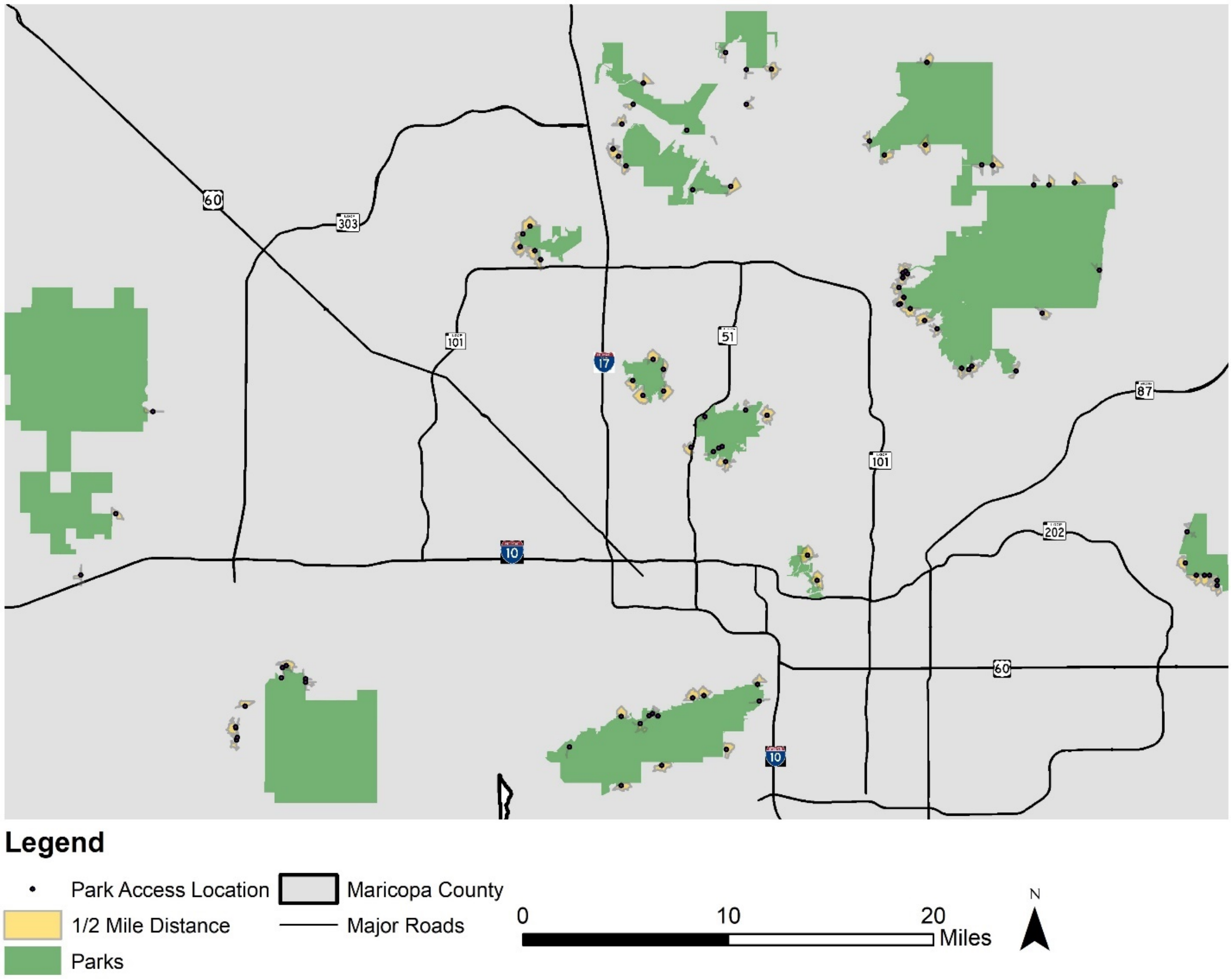

Figure 3. 5 Park Access

Species richness

The data shown in figure 3.6 are compiled from Arizona Game and Fish Department and The Nature Conservancy. Together, these data represent species richness represented in an ecological community, landscape or region. Species richness is simply a count of species, and it does not take into account the abundances of the individuals in each species or their relative abundance distributions. These data include birds, fish, mammals, and invertebrates. The darker green color shows where there are very high numbers of species. Most of the very high and high species counts are located in periphery sections of the metro area; however, there are places such as, South Mountain, Phoenix Mountain Preserve, Phoenix Sonoran Preserve, Salt River, Gila River and other parks located nearer the center of the region.

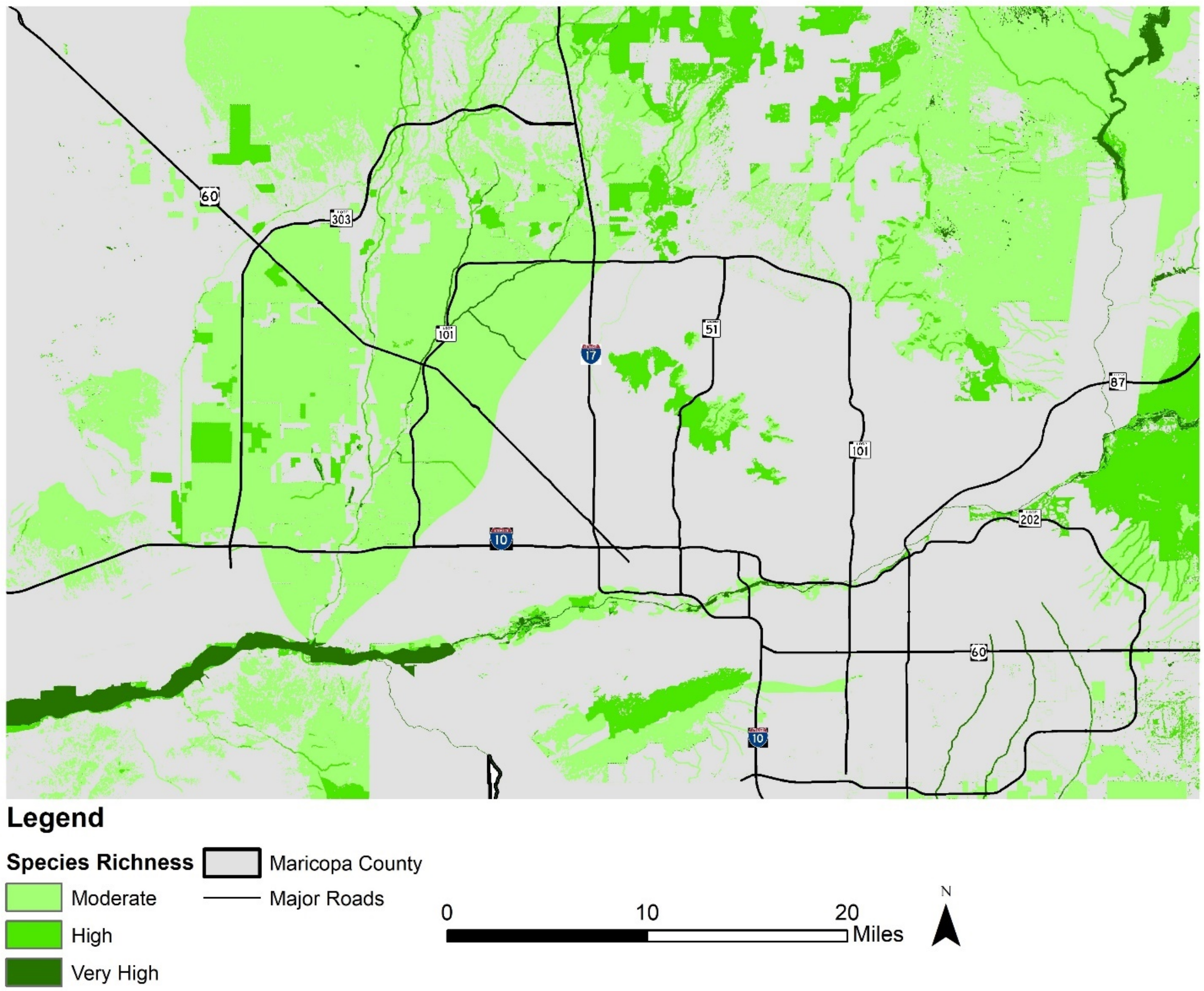

Figure 3. 6 Species Richness

The data shown in Figure 3.7 also are compiled from Arizona Game and Fish Department and the US Fish and Wildlife Service's National Wetlands Inventory. Riparian areas are plant communities contiguous to and affected by surface and subsurface hydrologic features of perennial or intermittent lotic and lentic water bodies (rivers, streams, lakes, or drainage ways). Riparian areas are usually transitional between wetland and upland. The riparian area is identified by the darker green color shown in figure 4.7. Small sections of riparian areas are found throughout the Phoenix metro; however, the main riparian areas follow the Verde River (east side of figure 4.7), which flows into the Salt River and eventually flows to the Gila River (south west of figure 4.7.

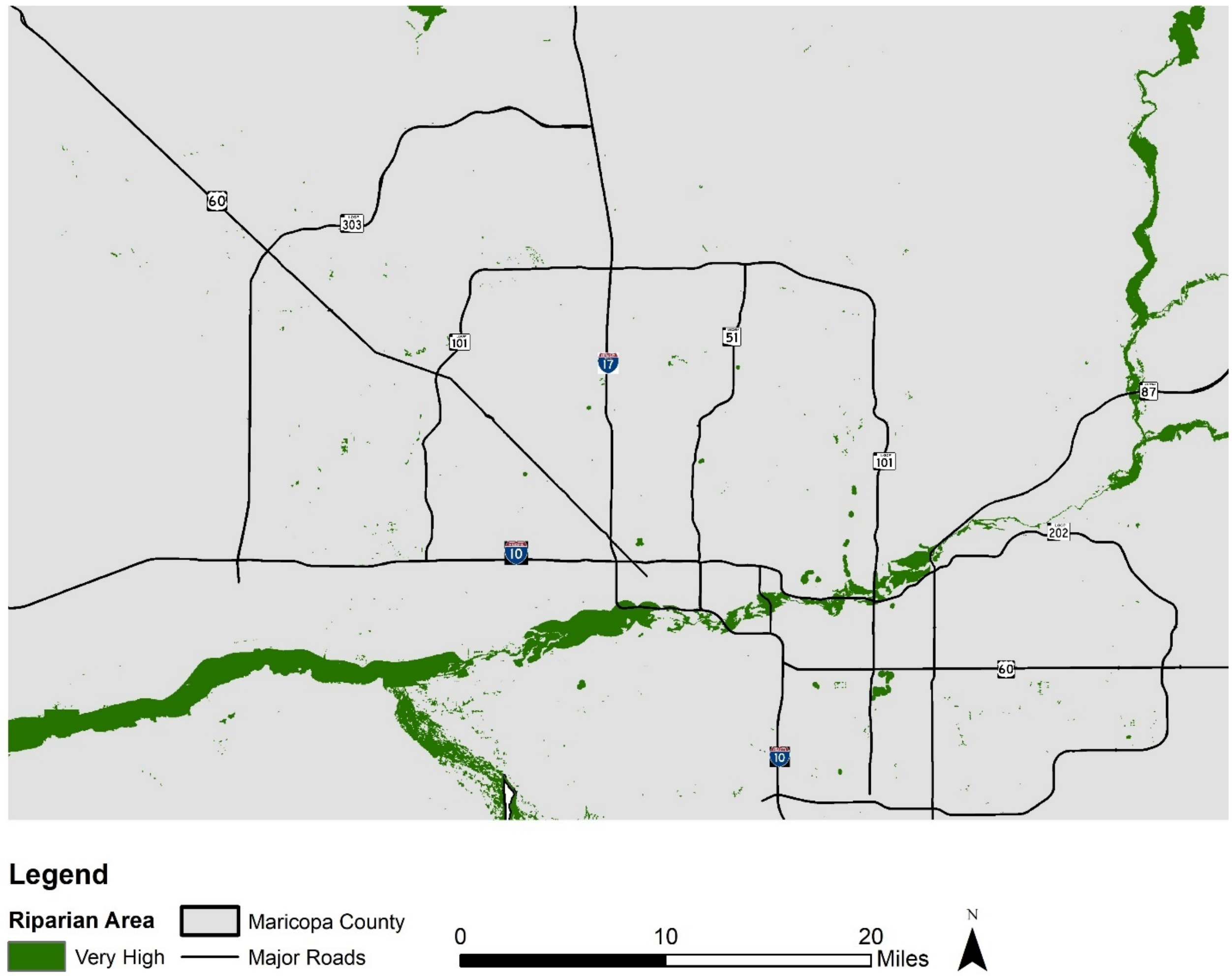

Figure 3. 7 Riparian Areas

3) Results / Discussion

The script ran giving a total of 190 corridors connecting between 20 different park locations throughout the region. The corridors found the least-costly route to each destination from each origin. Figures 4.1, 4.2, and 4.3 visualize the ecological, social, and the multifunctional layer used as the cost surface respectively.

The ecological layer is a combination of adding both the species richness and riparian area layers together. The data used from CAZCA shows which areas were considered to be ecological areas. CAZCA recorded the riparian areas as a 0 if there isn't a riparian area in that cell and a 5 if there is a riparian area there. The species richness layer was recorded as either moderate, high, or very high (3, 4, 5 respectively). The combinations of these numbers when adding them in the raster calculator allows for 3, 4, 5, 8, 9, 10, which is shown in Figure 4.1. The darkest blue layers recorded as 10 are the riparian areas that contain very high species richness. These are the areas that the path looks for when finding the least-cost path. Since the layer is showing 10 as being the most feasible, we took the inverse of each number and assigned the recorded 10 as a 1 and 9 as a 2 etc. This allowed for the model to search for land-uses that are assigned lower numbers and find the ecological layer cells assigned the lowest numbers or the least 'cost'.

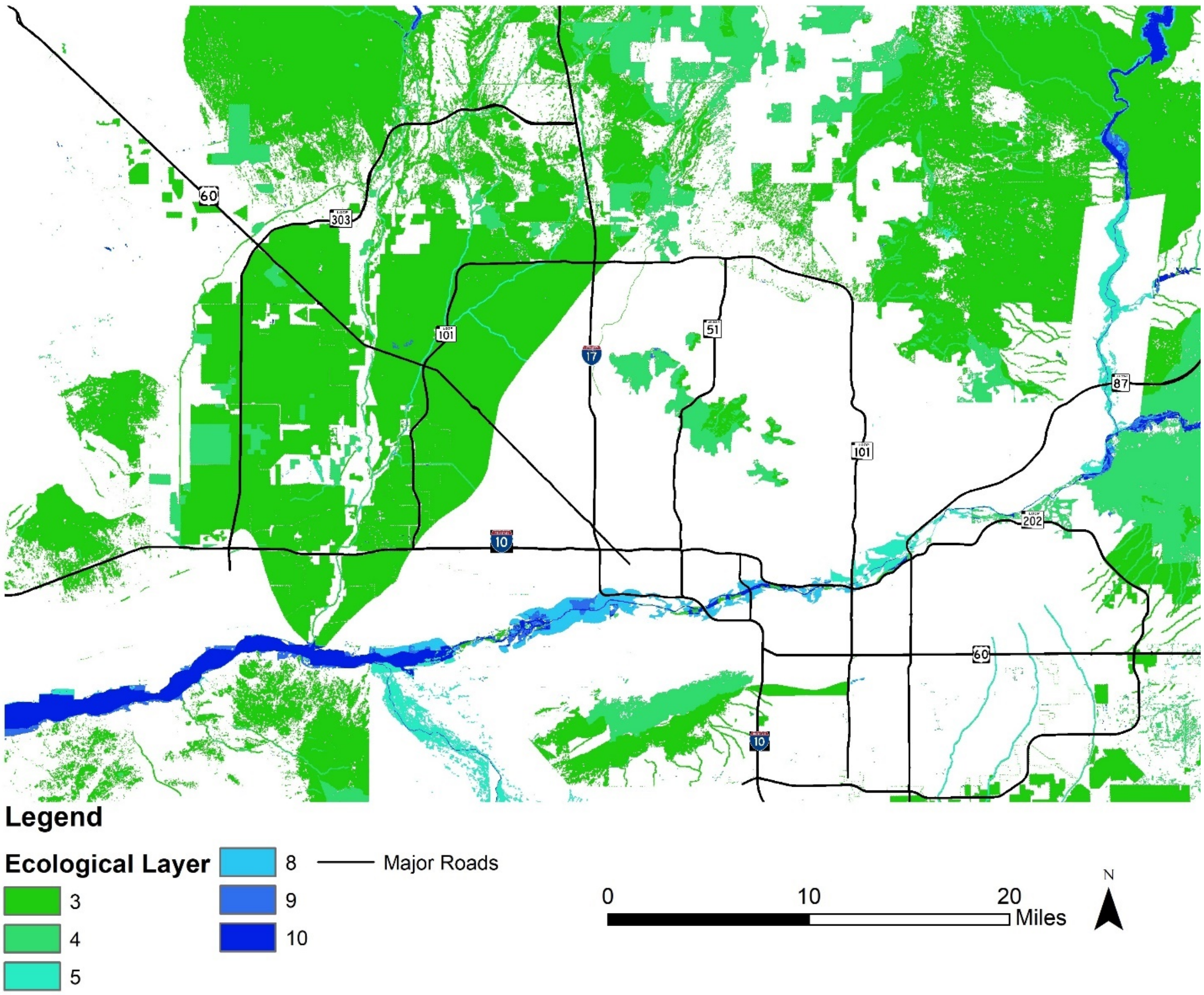

Figure 4. 1 Ecological Layer, combination of species richness and riparian area

The social layer is a combination of adding both, temperature vulnerability and park access, layers together. The data used shows areas that are more favorable than others. The more favorable areas are those that are not already within ½ mile walking distance to park entrances and the areas that have the highest recorded averages of days over 105°F. The temperature vulnerability data is seen in Table 4.2 This shows through natural breaks the total number of days that were assigned 1 – 5. The park access layer was recorded as a 5 if the cell is within ½ mile walking distance and a 0 otherwise. The combinations of these numbers when adding them in the raster calculator allows only for all numbers between 1 and 10, which is shown in Figure 4.2. The darkest red areas recorded as 10 are areas not within ½ mile walking distance to park access points and areas with high averaged days over 105°F. These are the areas that the path searches for when finding the least-cost path. Since the layer is showing 10 as being the most feasible we took the inverse of each number and assigned the recorded 10 as a 1 and 9 as a 2 etc. in the model. This allowed the model to search for land-uses, ecological rich areas, and socially vulnerable cells assigned with the lowest numbers.

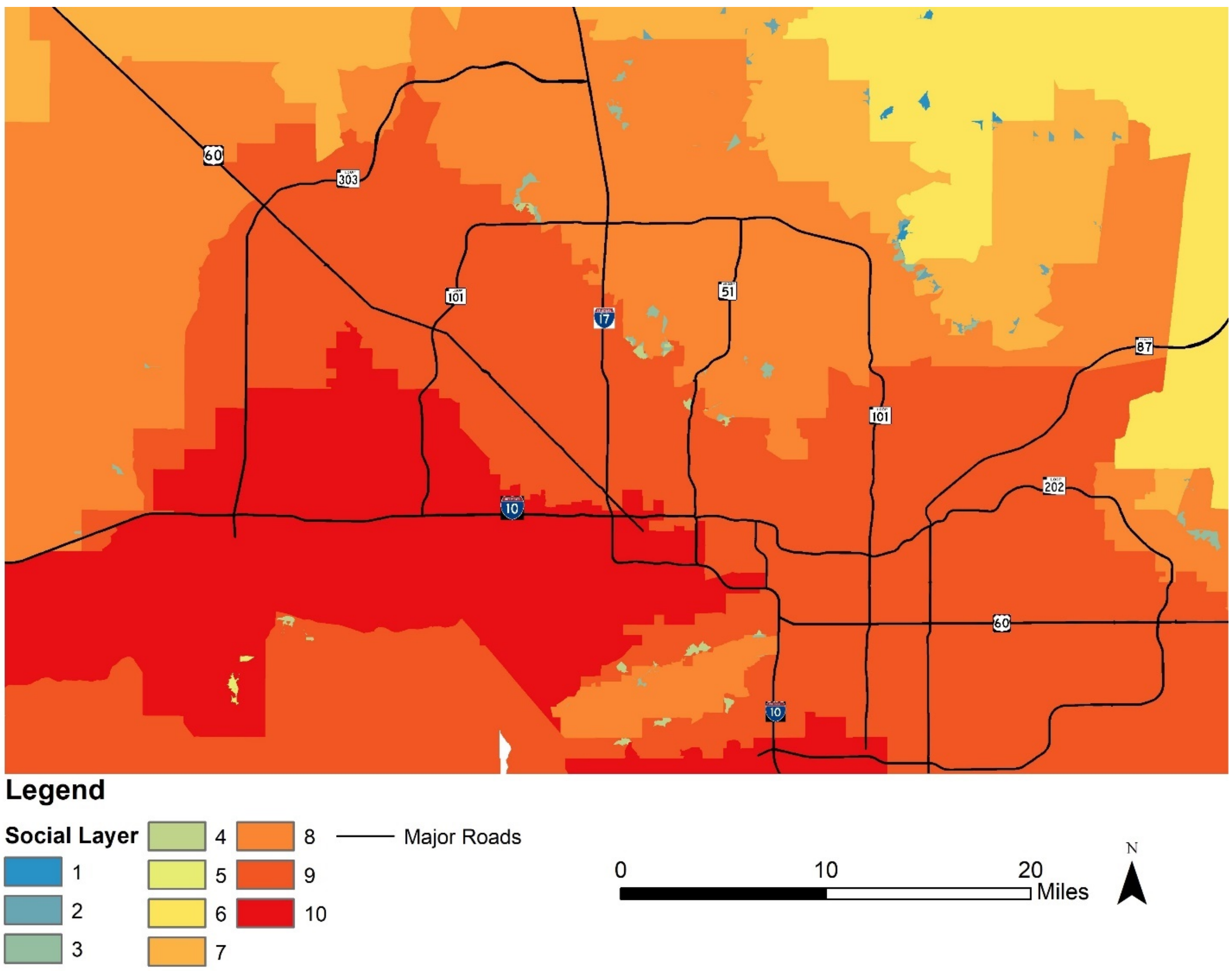

Figure 4. 2 Social Layer, combination of park access and temperature vulnerability

Figure 4.3 shows the combination of the ecological, social, land-use layers. All three layers had varying values between 1 and 10 and were used in the creation of the multifunctional cost layer. This multifunctional cost layer allowed the model to calculate where the least-costly direction and path to follow. A cell with a '1' for each of the three layers was where the path was looking for as it travels from the origin to destination. The blue colors shown in Figure 4.3 are lower 'cost' cells while the darker red color shows where there is more 'cost' to go through that cell. Figure 4.3 also shows the identified multifunctional corridors between origins and destinations. As the results show each path did in fact follow in the way that we would have hoped. They tend to follow the open spaces, vacant lands, and existing trails and bike paths nearer ecological areas and warmer temperatures while avoiding or going through the minimum number of more costly areas such as commercial, office, residential etc.

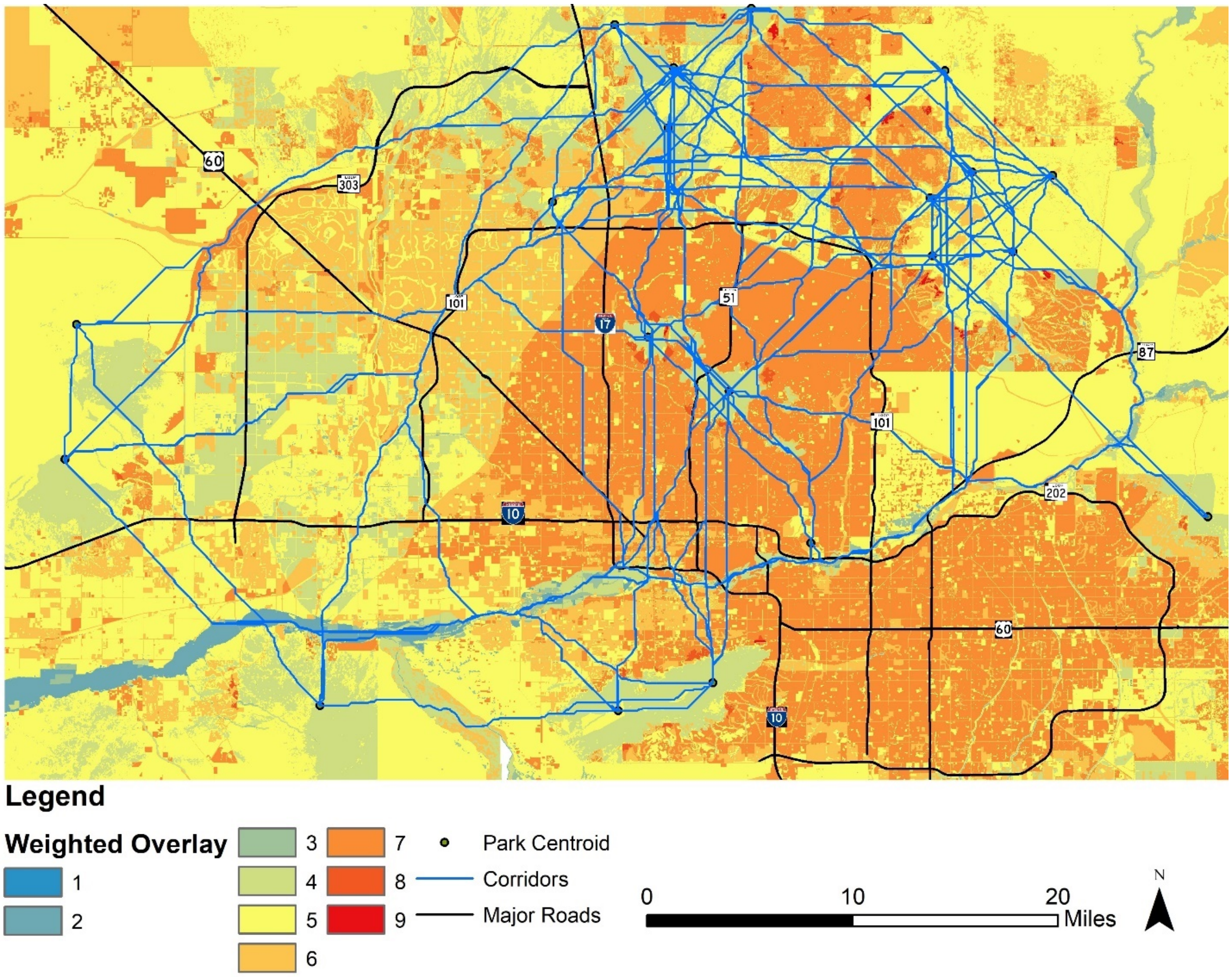

Figure 4. 3 Weighted Overlay with 190 Corridors

Looking more in depth at a single corridor connection we see that the path traveled from the southeast to the northwest of Figure 4.5. This corridor travels north through vacant land eventually connecting to the nearest existing canal path until it reaches a green open space. The path then finds the least costly-path across highway 51 and then eventually arrives at its destination. The total ‘cost’ is calculated on the path’s raster file, which totals up to be 370,303 and has a length of 13.5 miles. See Table 3.2 for descriptions for land-use codes.

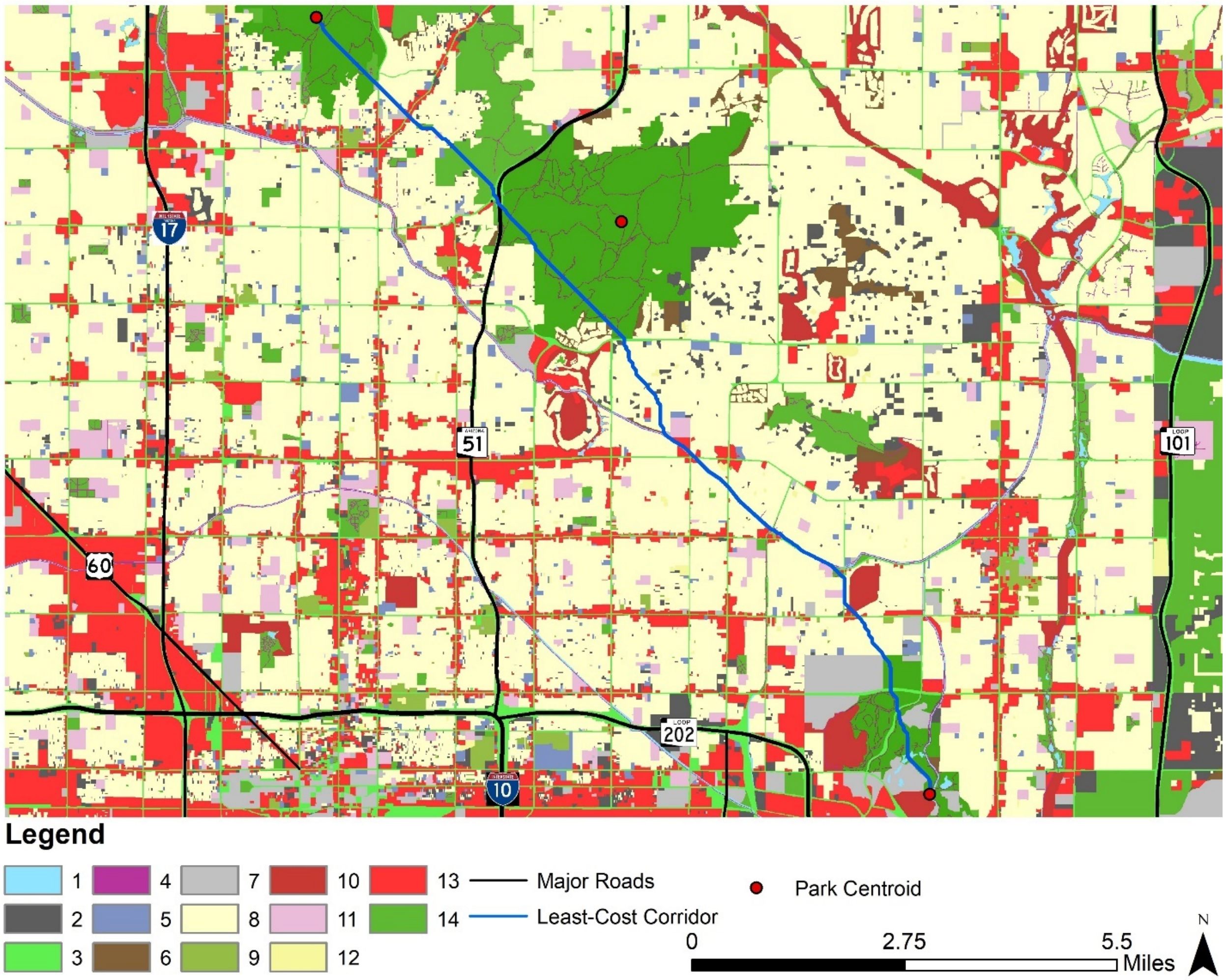

Figure 4. 4 Single Corridor Connection using the Multifunctional Layer as Cost Layer

The model was run a second time giving another 190 corridors connecting between the 20 parks with land-use as the cost layer rather than the weighted overlay of land-use, ecological, and social layers at 39, 34, 27 percent respectively. The second run took nearly 35 hours to complete. Figure 4.6 shows all corridors based solely on the land-use of the cost layer, which we term the feasibility corridors.

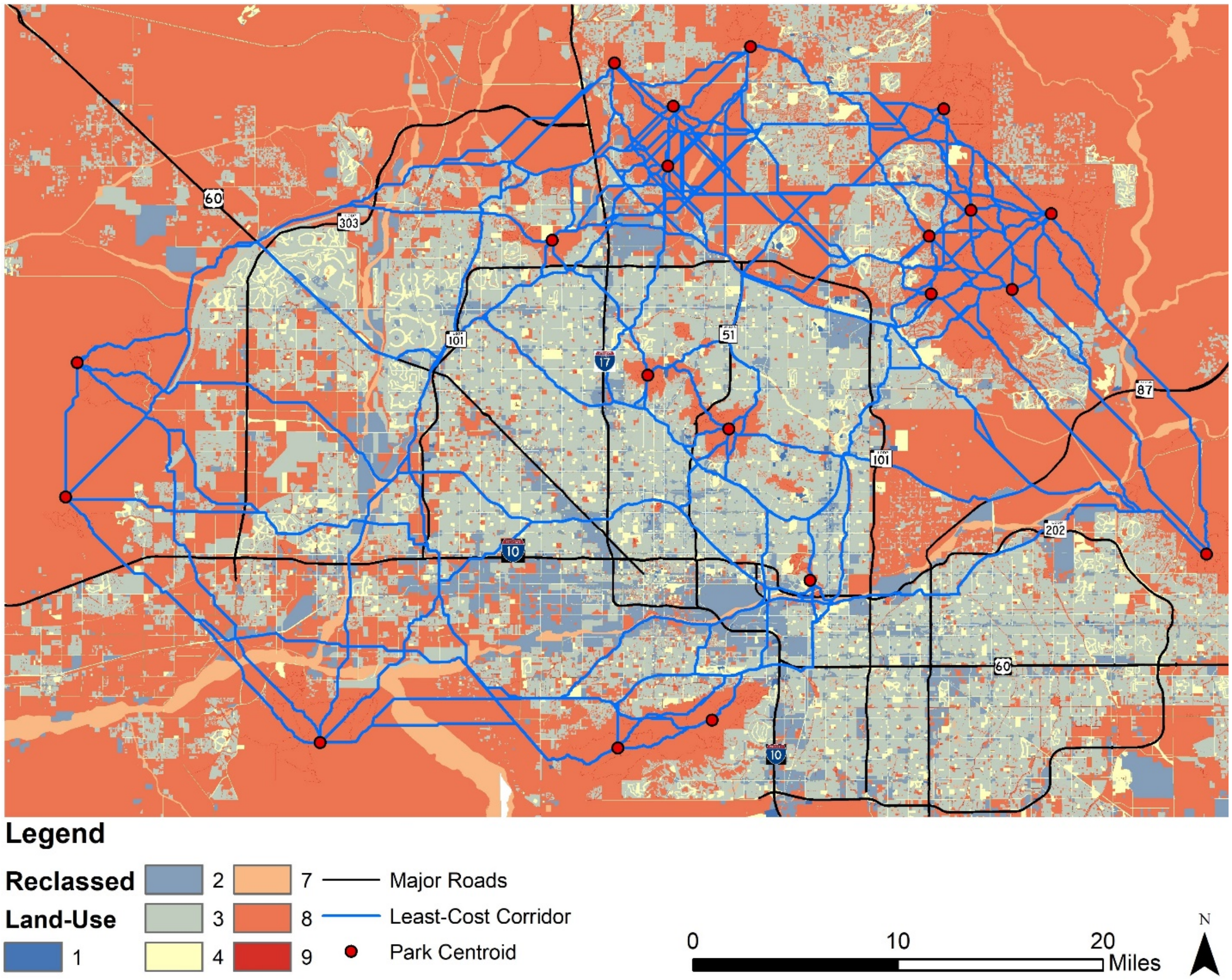

Figure 4. 5 Single Corridor Connection using the Feasibility Layer as Cost Layer

Figure 4.6 shows the comparison of the single path in Figure 4.4 and another path that travels from the same origin to the same destination. The blue line shows where the path travels when using all three (land-use, ecological, and social) layers (multifunctional corridor), while the purple line shows where the path travels with land-use as the only cost layer (feasibility corridor). When land-use is the only layer the total cost is less than the total cost from the feasibility layer in this case. This is because the land-use corridor is only searching for vacant land, bike trials, and other lower cost land-uses. While when all three layers are used as the cost layer the path not only needs to find the least costly land-use but needs to take into consideration the ecological land and higher average temperatures days. When the two paths split at the center of the map the multifunctional path follows more ecological land while the land-use cost corridor continues on an existing canal path. See table 3.2 for legend land-use code descriptions.

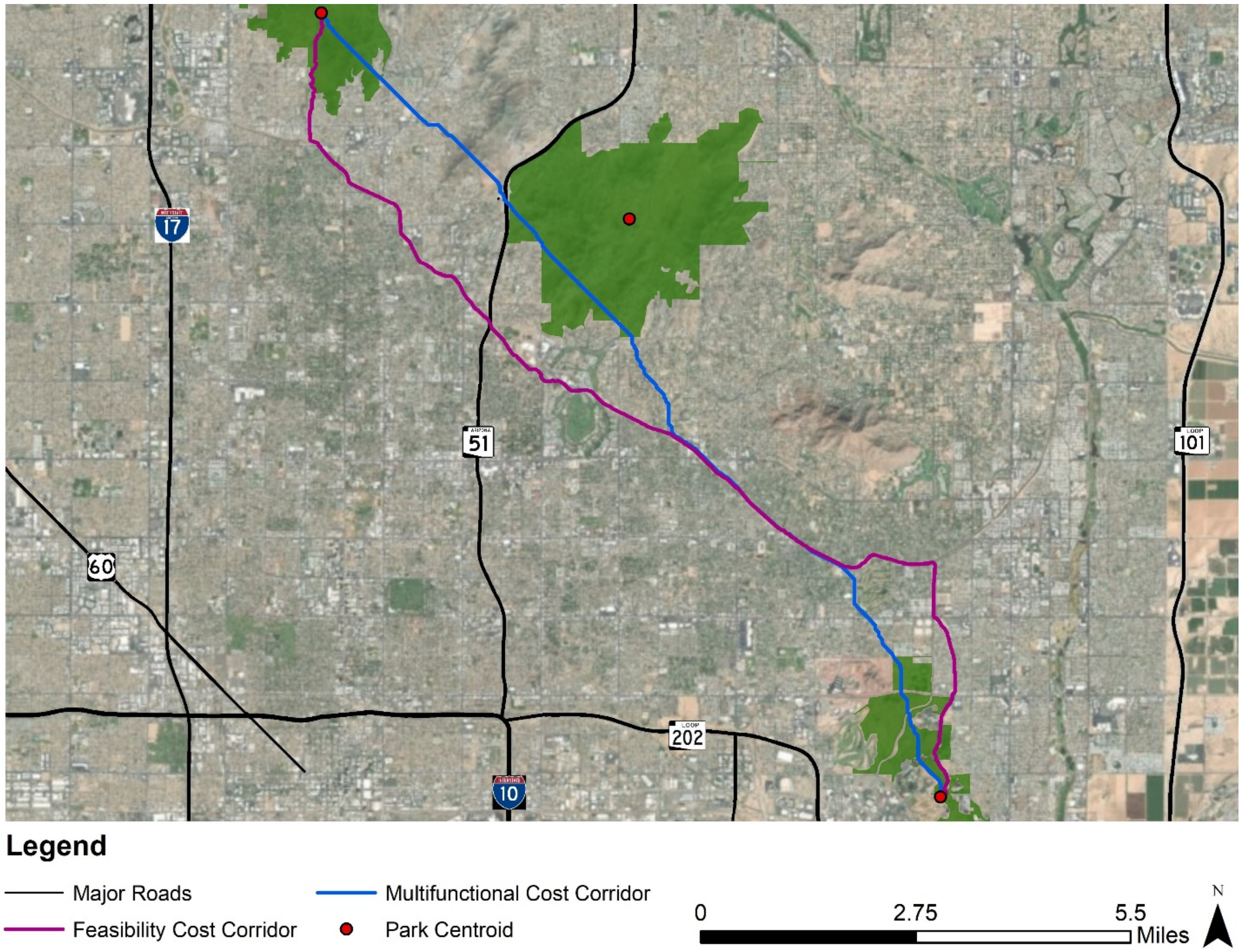

Figure 4. 6 Multifunctional Cost Layer Corridor Compared to Feasibility Cost Layer Corridor

Further discussion about future studies come from the survey respondents that sent emails with comments giving support and different data layers to add to the feasibility and multifunctional layers, they also gave additional data that may be useful in finding a least-costly path like historic / cultural properties and landmarks. Of the 12 people that gave comments on the survey 5 (41%) of them suggested land ownership should be one of the layers used. The comments given should be taken into consideration to bring about a more rigorous study to continue upon. Another way of doing this project would to actually assign a dollar cost to the cell/parcel that would need to be taken. Additional survey respondent comments see appendix. This cost information potentially could come from Maricopa tax assessor data. Having this information city officials could determine with a cost benefit analysis if a path should be developed on the land.

4) Recommendations / Conclusion

It is recommended that connections should be developed along existing paths, vacant land, and other open spaces that are accessible for public use. Most canal paths throughout the Phoenix metro tend to be simple dirt or asphalt paths that don't have much ecological benefit to them. Trees and other vegetation should be placed along canal paths to allow for biodiversity to use as connections and for cooling for residents that use such paths. These paths would be the first priority, along with vacant accessible land and other low-cost land-uses. An example of a multi-use corridor that Arizona American Society Landscape Architects (ASLA) designed in Mesa, Arizona looks to achieve a similar goal that this applied project does. ASLA designed a multi-use ecological corridor along loop 202 between Gilbert Road and Val Vista Road. An existing canal path south of loop 202 will also be used as another path for the project to increase connectivity. This project is to revitalize gravel mine lands into a natural landscape through implementation of green infrastructure, landscape ecology and restoring species habitat. Figure 4.8 illustrates where and how large the path will be (Chen, Vhung, & Kirby, 2016).

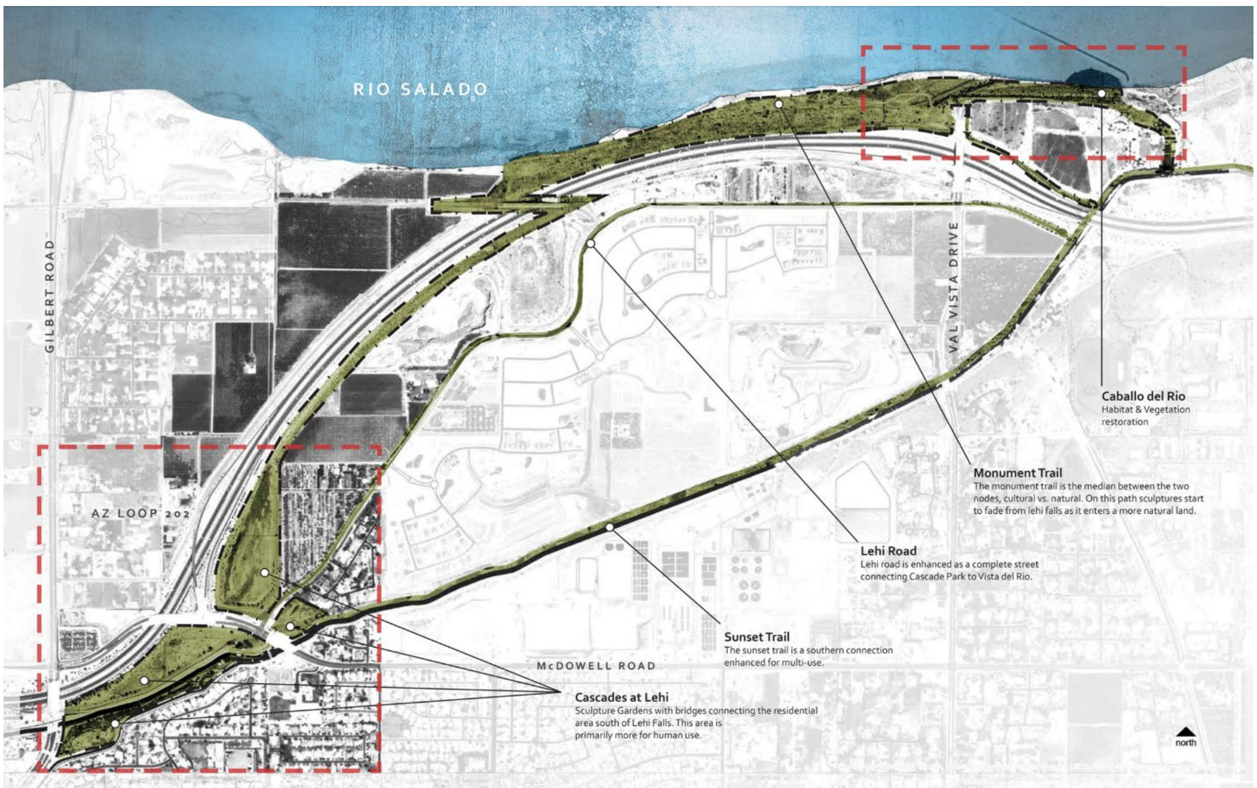

Figure 5. 1 Lehi Green Link (Mesa, Arizona)

This project models and prioritizes potential ecological and social corridors throughout the Phoenix, Arizona metropolitan area, using the least-cost path method. The model was done to provide researchers, planners, and other decision makers a method and an output that could guide planning efforts to enhance social and ecological connectivity across the metro region. Increasing connections between existing open spaces has the potential to provide residents and communities a space to recreate and lower stress, while also enriching and conserving biodiversity for native species.

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Appendix

Participant Recruitment Script:

Subject line for emails: Invitation to participate in research on multifunctional corridors to connect open spaces in Metropolitan Phoenix.

Dear {{First Name}} {{Last Name}},
I am a graduate student in ASU's School of Geographical Sciences and Urban Planning. For my master's capstone project, I am working with Professor Sara Meerow and the Central Arizona Conservation Alliance (CAZCA) to create a geospatial (GIS) model of existing open spaces and optimal paths for linking them with multi-use corridors to enhance social and ecological connectivity.

To complete the model, we need to know which land-uses would be most feasible to develop into corridors, and the relative importance of social and environmental priorities. We are asking diverse local experts to provide their professional opinions on these questions through an online survey.

Given your local knowledge, we ask that you complete a short (15) minute online survey. The results will be aggregated and used to finish the model. We know that you are very busy, and we appreciate your time. We will be happy to share the results with you. We believe this project can contribute to CAZCA's Regional Open Space Strategy and enhance connectivity planning in Maricopa County.

Survey:

Thank you for taking time to take this survey. My name is Caleb Carpenter and I am an urban planning graduate student under the direction of Professor Sara Meerow in the School of Geographical Sciences and Urban Planning at Arizona State University. I am currently working on my final applied capstone project, which focuses on identifying optimal social and ecological corridors and connections between open spaces in the Phoenix metropolitan area. This project is being conducted in collaboration with the Central Arizona Conservation Alliance (CAZCA) and will contribute to their Greenprint, an online mapping portal. Before you begin the survey, I would like to go over the purpose of the research, why your expert opinion and perspective is important, and how the information will be used.

The purpose of this research is to model potential paths and connections between existing open spaces. If implemented, these paths could provide many social and ecological benefits to our communities. This survey will help us determine which areas and land-uses would be most feasible to develop into multi-use paths and what areas should be prioritized in our model. We hope to gather a diversity of local perspectives and expertise.

The survey should last about 15 minutes. If you feel that you are not able to a question or would prefer not to answer it, feel free to skip the question. If you agree, I may contact you to participate in a follow-up to better understand your answers.

All answers and results in the survey are confidential. I will not associate your name with the results. All participants must be 18 or older. I will use the aggregated responses that you provide in my model, which will be part of my applied project.

This study has been reviewed and approved by the Arizona State University Institutional Review Board. If you have any questions about your rights as a subject/participant in this research, or if you feel you have been placed at risk, you can contact the institutional Review Board, through the ASU Office of Research Integrity and Assurance, at (480) 965-6788.

If you have any questions about who I am or how your results will be used please contact me at cjcarpe7@asu.edu, or Sara Meerow at Sara.Meerow@asu.edu.

Question 1)
In order to identify potential corridors to connect existing open spaces we first want to compare which land-uses would be more or less feasible to develop into corridors.

Please score each land-use from 1 to 10, with 1 being the least costly to acquire and develop into a corridor and 10 being the most costly.

You can assign the same number to multiple land-uses. Before assigning any scores please read through the full list of land-uses to get an understanding of relative costs. For example, open spaces might be seen as quite easy to connect so a score of 1 would prioritize those areas.

___ Trails and Bike Paths
___ Open Space / Agriculture
___ Golf Course
___ Residential
___ Transportation
___ Developing Residential / Employment
___ Vacant Land
___ Commercial/Industrial/Office/Hotel/Resort/Airport/Mixed-use
___ Special Event/Military
___ Passive/Restricted Open Space/Undevelopable
___ Religious/Institutional
___ Educational
___ Medical/Nursing Facilities
___ Water Bodies

Question 2)
In addition to land-use we want to incorporate ecological and social priorities into our model.

Please score the relative importance of the two ecological layers below from 1 to 10, with 1 being the lowest priority and 10 highest priority. Each number can be used more than once. Before starting to compare them please read through both descriptions of the ecological layers.

Species Richness - This layer represents species richness in an ecological community, landscape or region. Species richness is simply a count of species, and it does not take into account the abundances of the individuals in each species or their relative abundance distributions. These data include birds, fish, mammals, and invertebrates. The data are compiled from Arizona Game and Fish Department and The Nature Conservancy.

Riparian Areas - This layer represents riparian areas, plant communities contiguous to and affected by surface and subsurface hydrologic features of perennial or intermittent lotic and lentic water bodies (rivers, streams, lakes, or drainage ways). Riparian areas are usually transitional between wetland and upland. Riparian areas have one or both of the following characteristics: 1) distinctly different vegetative species than adjacent areas, and 2) species similar to adjacent areas but exhibiting more vigorous or robust growth forms. The data are compiled from Arizona Game and Fish Department and the US Fish and Wildlife Service's National Wetlands Inventory.

___ Species Richness
___ Riparian areas

Question 3)
In addition to land-use we want to incorporate ecological and social priorities into our model.

Please score the relative importance of the two social layers below from 1 to 10, with 1 being the lowest priority and 10 highest priority. Each number can be used more than once. Before starting to compare them please read through both descriptions of the social layers.

Heat Vulnerability - This layer identifies hotspots across the region. It consists of high resolution near-surface air temperature aggregated to the block group level.

Park Access - This layer identifies areas of park poverty, or those lacking a park within a 10-minute walk or 1/2 mile.

___ Heat Vulnerability
___ Park Access

Question 4)
Now that the three layers have been ranked individually, in your professional opinion what would the weighting of each of those layers be (from 0 to 100 percent)? In other words, the land-use, social, and ecological layers are x%, y%, and z% respectively and total up to 100%.

Land-use Layer	____
Social Layer	____
Ecological Layer	____
Total:	100%

Question 5)
Do you know of any other data that should be included in one of the three (land-use, social, ecological) layers? If so, please indicate below. Also, if you have any other comments feel free to write them below.

Question 6)
What organization do you work for?

Question 7)
What is your job title?

Question 8)
May we contact you if we have follow-up questions? If so, please provide your email. We will also send you a copy of the final report.

Survey Responses Averages

Question 1)
2 - Trails and Bike Paths
3 - Open Space / Agriculture
6 - Golf Course
7 - Residential
6 - Transportation
7 - Developing Residential / Employment
3 - Vacant Land
8 - Commercial/Industrial/Office/Hotel/Resort/Airport/Mixed-use
7 - Special Event/Military
3 - Passive/Restricted Open Space/Undevelopable
6 - Religious/Institutional
6 - Educational
8 - Medical/Nursing Facilities
4 - Water Bodies

Question 2)
7 - Species Richness
8 - Riparian Areas

Question 3)

6 - Heat Vulnerability
7 - Park Access

Question 4)
39% - Land-use Layer
34% - Ecological Layer
27 % - Social Layer

Question 5)

1. Geological, social importance, tribal importance, military impact
2. Instead of land use, I'd suggest you map out ownership/institutions, as some will be very hard to negotiate (private or State Trust land), and others may be easier. Also, species richness is not particularly interesting for conservation reasons, because non-native species are included in any richness count. For example, you can have a very biodiverse but 100% non-native ecological community that would not be particularly interesting from a conservation point of view. I'd map out where native landscapes / native vegetation is -- that will be important for native mammal or other species of conservation concern.
3. Poverty rate; life expectancy
4. Zoning, subdivision, traffic volume, land value, stage of development, general plan designation, length of corridor,
5. Plans need to be made upfront in the zoning of individual governments and landowners. Public support also needs to be organized in mass for the open/space trails etc. goals.
6. Publicly Owned Property
7. Species diversity in addition to richness
8. Geodiversity: the concept is that areas of high geodiversity (topography, drainage, water features, substrates, etc.) are more resilient to ecological stressors. They are also more scenically valued. See NAUs Paul Beiers work on this topic.
9. Land Ownership and easements are necessary to successful implementation
10. Cultural resources
11. Open space and agriculture should be treated as separate uses as agriculture has a huge impact on the environment and resource use
12. Land Ownership and easements are necessary to successful implementation

Criteria	Methodology	Description	Data Source
Land-Use	This data layer was downloaded from Maricopa Association of Governments (MAG) and condensed into 14 different land-use types rather than 30. They were condensed together for the survey that was sent to the regional experts.	This layer is split into 14 different land-use types. (trails and bike paths, open space/agriculture, golf course, Residential (single-/multi-family), Transportation, developing residential/employment, vacant land, commercial/industrial/office/hotel/resort/airport/mixed-use, special event/military, passive/restricted open space/undevelopable, religious/institutional, educational, medical/nursing facilities, water bodies)	-Maricopa Association of Governments (MAG) 2016
Open Space Centroid	203 parks / open spaces were identified through a definition query of 30 acres or larger. The selected park parcels were then change from polygon to point layer. The point is located at the centroid of each park.	This layer has 203 open spaces / parks that are 30 acres or larger throughout the Phoenix metropolitan area.	-Maricopa Association of Governments (MAG) 2016
Species richness	Result value = 1-5 1. SHCGSGCN FINAL_NoTribal resampled to 5m 2. Reclassify to give NoData 0 value, all other values remain the same as original raster 3. ESA richness from TNC 2010 freshwater assessment buffered 20m 4. ESA richness data reclassified 3,4,5 based on natural breaks of # of species 5. Spikedace crit hab lines buffered 20m 6. All other AGFD crit hab polygon data merged with spikedace buffers, converted to raster and given value of 5 7. All data combined with cell statistics maximum *AGFD crit hab in study area: Spikedace, acuna cactus, chiricahua peop forg, gila chub, mexican, mex spotted owl, narrowheaded, yellow billed cuckoo, razorback sucker, sonora chub, sw willow flycatcher	The data shown here are compiled from Arizona Game and Fish Department and The Nature Conservancy. Together, these data represent species richness represented in an ecological community, landscape or region. Species richness is simply a count of species, and it does not take into account the abundances of the individuals in each species or their relative abundance distributions. These data include birds, fish, mammals, and invertebrates.	-Arizona Game and Fish Department (AZGFD) - The Nature Conservancy (TNC)
Riparian Areas	Result value = 5 1. Resample SHCGRiparianFINAL_NoTribal to 5m. Data has value of 5. (we were given revised data ~March 28, 2017, but switched back to original data on 4/18) 2. Pull riparian areas out of AZGFD modified ReGap data - value 124 reclassified to 5 (80, 83, 84, 85 are riparian but not in study area) 3. NWI Riparian data converted to raster and given value 5 4. Data combined with cell statistics maximum (prioritization of AGFD data provided by AGFD)	The data shown here are compiled from Arizona Game and Fish Department and the US Fish and Wildlife Service's National Wetlands Inventory. Riparian areas are plant communities contiguous to and affected by surface and subsurface hydrologic features of perennial or intermittent lotic and lentic water bodies (rivers, streams, lakes, or drainage ways). Riparian areas are usually transitional between wetland and upland. Riparian areas have one or both of the following characteristics: 1) distinctly different vegetative species than adjacent areas, and 2) species similar to adjacent areas but exhibiting more vigorous or robust growth forms.	- AZGFD -Fish and Wildlife Service (FWS) National Wetlands Inventory
Heat Vulnerability	Extreme heat was created by using the map algebra tool in ArcGIS to calculate, for each raster cell, the number of days the max temperature was over 105F. Then, the data was converted to block groups from its point using the "Extract by Point" tool to assign values calculated in the first step to block group centers. The aggregated data was then changed from vector to raster data at 10 by 10-meter cell size.	This layer identifies hotspots across the region. It consists of high resolution near-surface air temperature aggregated to the block group level. The data is a 10-year average (2008-2017) with days of highest temperature exceeding 105F.	Turner, D.P., W.D. Ritts, and M. Gregory. 2017.
Park Access	Each park in the region was changed from polygon to point feature creating access points to each park. These points were then put into the network analyst tool to calculate distance from each point. A road network was created in ArcMap for the network analyst tool to run from each park access point following the road network (Manhattan distance) ½ mile from its starting point.	This layer identifies areas of park poverty, or those lacking a park within a 10-minute walk or 1/2 mile.	Arizona State University Network Analyst street data.