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Article

Urban Park Systems to Support Sustainability: The Role of Urban Park Systems in Hot Arid Urban Climates

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Abstract: Quantifying ecosystem services in urban areas is complex. However, existing ecosystem service typologies and ecosystem modeling can provide a means towards understanding some key biophysical links between urban forests and ecosystem services. This project addresses broader concepts of sustainability by assessing the urban park system in Phoenix, Arizona's hot urban climate. This project aims to quantify and demonstrate the multiple ecosystem services provided by Phoenix's green infrastructure (i.e., urban park system), including its air pollution removal values, carbon sequestration and storage, avoided runoff, structural value, and the energy savings it provides for city residents. Modeling of ecosystem services of the urban park system revealed around 517,000 trees within the system, representing a 7.20% tree cover. These trees remove about 3630 tons (t) of carbon (at an associated value of $285,000) and about 272 t of air pollutants (at an associated value of $1.16 million) every year. Trees within Phoenix's urban park system are estimated to reduce annual residential energy costs by $106,000 and their structural value is estimated at $692 million. The findings of this research will increase our knowledge of the value of green infrastructure services provided by different types of urban vegetation and assist in the future design, planning and management of green infrastructure in cities. Thus, this study has implications for both policy and practice, contributing to a better understanding of the multiple benefits of green infrastructure and improving the design of green spaces in hot arid urban climates around the globe.

Keywords: ecosystem services; ecosystem modeling; sustainability; human health; environmental quality; hot arid urban climate

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1. Introduction

Urban forests within urban park systems provide essential buffering ecosystem services for the sustainability of rapidly urbanizing cities. Ecosystem services are those ecological functions, provided by ecosystems for free, that society values for their supply of public goods including ecosystems' ability to provide essential provisioning, regulating, supporting, and cultural services [1,2]. Rapid urbanization, in places like Phoenix, Arizona (AZ), delete or degrade endemic ecosystems and replace them with novel biogeophysical compositions and configurations. Rapid urbanization is a global phenomenon that also results in more people living in cities being exposed to hazards from urbanization. From 1950 to 2010, urban residents increased from 29% to 50% globally and by 2050 the proportion of urban residents is expected to reach 69% of the global population, which represents 6.3 billion people. Thus, urban forests are key to protecting the health and well-being for most people around the world [3]. Urban parks are dedicated islands within urbanized areas to nurture much-needed ecosystem services in cities. Other urbanized lands are dedicated to grey infrastructure (i.e., buildings and pavement) that are primarily composed of mineral-based materials, which seal soils and alter important biogeochemical processes. City residents need these critical urban park systems to cool and clean the air, sequester and store carbon, absorb and clean runoff, enhance biodiversity, and reduce energy demands [4]; all problems resulting from grey infrastructure. For example, urban-induced warming (i.e., urban heat island effect) results from constructing buildings and pavements, replacing unbuilt landscapes that previously maintained endemic heating and cooling processes [5].

In rapidly urbanizing cities, like the Phoenix Metropolitan Area (PMA), urbanization has already caused some impoverished, tree-poor, compact neighborhoods' temperatures to be up to 6.4 °C warmer than better-off neighborhoods with a wealth of trees and vegetation [6]. The pace of urbanization is intimately linked with urban-induced warming and has been found to accelerate the urban heat island (UHI) phenomena [5]. Brazel and colleagues [7] found that in Phoenix, rapid urbanization, warmed the air temperature in June by 1.4 °C per 1000 homes constructed. Urban-induced warming is made worse when combined with global climate change due to increasing concentrations of greenhouse gases. These two mechanisms will continue to warm rapidly growing cities during this century. On top of urban-induced warming, the continental U.S. average temperatures have increased by 1.3 °F to 1.9 °F since record keeping began in 1985. This global warming has resulted in more intense and frequent heat waves, and the future likely holds more extreme heat. Annual average U.S. temperatures are projected to increase by 3 °F to 10 °F by the end of the 21st century, depending on future emissions of greenhouse gases and other regional factors [8]. Together, warming from both urban-induced and global temperature increases has the potential to make many urban neighborhoods unsustainable. People residing in hot neighborhoods are more vulnerable to heat exposure because they have fewer social and material resources to cope with extreme heat [6]. Cities around the world are facing various urban problems driven by increasing urban populations, urban-induced warming, and climate change [9]; urban park systems play a key role in addressing those negative urban problems.

Urbanization is key driver of changes in ecosystem services. For these reasons, policy makers, academics, urban planners and engineers have started to focus on the ecosystem services required to move toward urban sustainability [10]. Yet, advocates require more convincing and empirically driven evidence on the social, environmental, and economic return on capital investments in propagating and managing healthy urban forests. In arid cities, it is not just an investment in urban forests, but also the water needed to maintain those forests. Stronger justification and evidence are needed in arid cities where water availability is a critical sustainability issue. Urban forests in cities across the country are important for sustainable futures by improving numerous environmental and social aspects of cities, including human health, walkability, thermal comfort, cultural desires, stormwater management, air quality, wildlife habitat, aesthetics and carbon sequestration. For urban forestry, the challenge cities face includes understanding and clearly illustrating the value trees provide to society and how cities should fund effective urban forestry management programs. Quantifying ecosystem services in urban areas is complex. However, existing ecosystem service typologies and ecosystem modeling can provide a means towards understanding some key biogeophysical links between urban forest and ecosystem services [11]. The overall objective of this project is to improve our understanding of the complex interrelationships between ecosystem services, human health and well-being to craft multiple forestry strategies that support sustainable futures. This project addresses the broader concept of sustainability by assessing the value of an urban park system in Phoenix, Arizona (AZ), USA.

The purpose of this study is to quantify and demonstrate the multiple ecosystem services provided by Phoenix's green infrastructure (i.e., urban park system), including air pollution removal, carbon sequestration and storage, avoided runoff, structural value, and energy savings for residents in the city's hot arid urban climate. In particular, Phoenix's hot arid urban conditions provide a glimpse at what many rapid urbanizing cities around the globe may face from global climate change and urban-induced warming in the 21st Century. This study will assess the status of Phoenix's existing urban park system's forest to estimate the environmental benefits and ecosystem services provided, thus improving our understanding of the role trees play in creating healthy, livable, and sustainable cities [12]. Modelling urban forest structure provides useful information for estimating the total leaf area, tree and leaf biomass, and quantifying the numerous ecosystem services and forest functions; accurate assessments are critical for managers and planners to understand how the various ecosystem services improve both environmental quality and human health and well-being in urban areas [13]. Though urban forests perform many functions and add value to many aspects of everyday life, currently only a few of these attributes can be accessed due to our limited ability to quantify all of these values utilizing standard data analyses [14].

The most precise way to assess urban forests is to measure and record every tree on a site, but although this works well for relatively small areas such as a single street with trees and small parks it is prohibitively expensive for large tree populations [13]. Instead, random sampling techniques offer a cost-effective way to assess urban forest structure and ecosystem services for large-scale assessments [13]. Comprehensive assessments of urban forest structure are thus commonly conducted using sampling techniques (e.g., [15–20]). To facilitate this approach, the U.S. Forest Service's Northern Research Station developed the i-Tree Eco model (formerly known as the Urban Forest Effects model) to support assessments of urban forest structure, ecosystem services, and economic benefits [21]. The i-Tree Eco model incorporates protocols to measure and monitor urban forest structure and estimate its ecosystem functions and economic values; the associated software utilizes standardized field data from randomly located plots and local hourly air pollution and meteorological data to quantify urban forest structure and its numerous effects [13]. The i-Tree model is already used in over 50 cities to assess urban forest structure and functions using a standardized approach (see, for example [20,22,23]). The study utilized i-Tree Eco to assess the urban park system's forest structure and ecosystem services in the City of Phoenix, AZ, USA.

2. Methods

In terms of the science and mechanics of modeling ecosystem services, the starting point is understanding forest structure—the extent, distribution and composition of urban forest. Urban forest assessment is essential for developing a baseline from which to measure changes and trends. Managing the urban forest includes tree maintenance, policy development, and budgetary decisions—all of which depend on understanding current urban forest conditions [12]. There are two ways of assessing urban forest structure using both on-the-ground measurements and remote sensing analysis. An accurate quantification of urban forests can help in understanding the various ecosystem services and values it provides [13]. Top-down (aerial) approaches produce good cover estimates and can detail and map tree and other cover locations; however, they tell little about composition and therefore little about services provided. Bottom-up (field inventory) approaches provide detailed management information, such as number of trees, species composition, tree sizes and health, tree locations, and risk information. This approach provides better means to assess and project ecosystem services and values into the future. This bottom-up approach is the foundation of i-Tree Eco and thus was the approach utilized for this study.

i-Tree Eco allows users to inventory or sample tree populations anywhere and at any scale (single tree to large region) to estimate tree populations (e.g., number of trees, species composition). It then combines local weather and pollution data to estimate ecosystem services and values by simulating the trees under local conditions using local tree data. The i-Tree Eco software is designed to apply standardized field data from randomly located plots and local hourly air pollution measures and meteorological data (e.g., volatile organic compound emission, air pollution removal by the urban forest, relative ranking of species' effects on air quality, tree transpiration) to quantify: (1) the structure of urban forests and the resulting effects on local air quality; (2) runoff, stream flow and water quality; (3) building energy use; (4) carbon sequestration; and (5) air temperatures. The methodological framework of the i-Tree Eco model is based on an assessment of the urban forest structure, function, and value.

In the City of Phoenix, 50 (0.04 ha) plots were sampled using a random sampling method across the urban park system made up of both publicly- and privately-owned land parcels (Figure 1 and Table 1). Phoenix has a number of master plan gated communities that represent the privately owned and managed neighborhood parks that were included in the study. Plots were permanently referenced so that they can be monitored over time and were assigned proportionate to the land area within each stratum based on land use zoning. All field data were collected during the 2016 vegetation period (May–June) to properly assess the tree canopy health. At each field plot, three crew members collected data on ground vegetation and tree cover, individual tree attributes such as species, stem diameter, height, crown width, crown canopy missing and dieback, and their distance and orientation to neighboring buildings [13]. Field data was input into the i-Tree Eco model to assess forest structure and the associated ecosystem services and values. The initial field data analysis was conducted using i-Tree Eco with assistance from scientists and staff at the United States Department of Agriculture (USDA) Forest Service's Northern Research Station and the Davey Tree Expert Company. Additional analyses were undertaken by project researchers to explore information of specific interest for Phoenix. Details of the i-Tree Eco methods are available at the i-Tree website (www.itreetools.org) and in several publications (e.g., [13,24,25]).

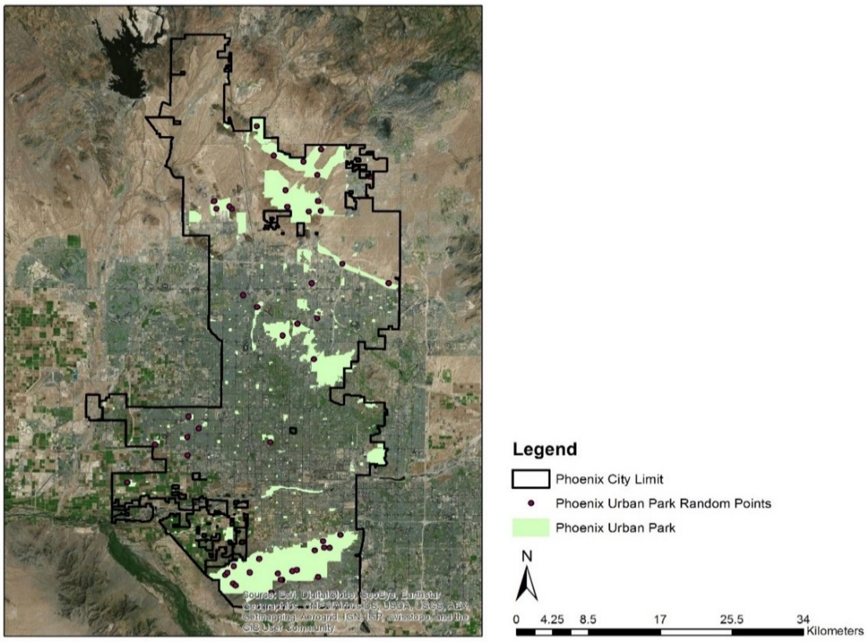

Figure 1. Urban park system plot locations within publicly and privately owned land parcels, City of Phoenix, Arizona, USA.

Hourly weather data are collected to analyze air pollution removal by the urban forest, such as volatile organic compound emissions, air pollution removal by the urban forest, relative ranking of species' effects on air quality and tree transpiration [24]. Air pollution removal estimates are derived from calculated hourly tree-canopy resistance for ozone, and sulfur and nitrogen dioxides based on a hybrid of the big-leaf and multi-layer canopy deposition models [26,27]. Recent updates to the air quality models are based on improved leaf area index simulations, weather and pollution processing and interpolation, and updated pollutant monetary values. To calculate current carbon storage levels, the biomass for each tree is calculated using published allometric equations and measures of tree data [22,28]. Carbon storage and carbon sequestration values are based on estimated or customized local carbon values. Carbon storage and carbon sequestration values in Phoenix are calculated based on $78 per ton [29].

Annual avoided surface runoff is calculated based on rainfall interception by vegetation, specifically the difference between annual runoff with and without vegetation. Estimates are made of the percent of the area beneath the dripline of the tree that is impervious or occupied by shrubs. Although tree leaves, branches, and bark may intercept precipitation and thus mitigate surface runoff, only the precipitation intercepted by leaves will be taken into account in this study. The value of avoided runoff is based on estimated local values based on the United States Forest Service's Community Tree Guide Series [30]. Structural values were based on the valuation procedures utilized by the Council of Tree and Landscape Appraisers, which uses tree species, diameter, condition, and location information [31]. Structural value is based on four tree/site characteristics: (1) trunk area (cross-sectional area at diameter at breast height); (2) species; (3) condition; and (4) location. Trunk area and species will be used to determine the basic value, which is then multiplied by condition and location ratings (0 to 1) to determine the final tree compensatory value. The seasonal effects of trees on residential building energy use are calculated based on procedures described in the literature [32] using the distance and direction of trees from residential structures, tree height, and tree condition data. To calculate the monetary value of energy savings achieved, local or custom prices per Megawatt-hour (MWH) or One million British Thermal Units (MBTU) are utilized. One measure of the relative dominance of species in a forest community is called the Importance Value (IV). IV ranks species within a site based upon three criteria: (1) how commonly a species occurs across the entire forest; (2) the total number of individuals of the species; and (3) the total amount of forest area occupied by the species [33]. IV is calculated as the sum of relative leaf area and relative composition. To compare forest communities' composition that may differ in size, or that were sampled at different intensities, IVs are calculated using relative rather than absolute values.

Urban forest ecosystem functions' quantification procedures are estimated based on various algorithms and many of the ecosystem functions estimated by the i-Tree Eco model are difficult to accurately measure in the field; thus, modeling procedures are needed to quantify these effects for urban forests [13]. Due to the importance of the quality assurance of field data accuracy, the model estimates are only as good as the field data inputs; the i-Tree Eco model estimates current urban forest structure and functions and then treats this as a permanent average value for the plot [13]. Urban forest conditions are changeable, so the model value is not absolute; it represents a snap shot in time. The precision and cost of the estimate is also dependent on the sample and plot size. Generally, 200 plots (0.04 ha each) in a stratified random sample (with at least 15 plots per stratum) will produce a 12% relative standard error for an estimate covering the entire study area [25]. As the number of plots increases, the standard error decreases and the method provides more accurate population estimates. However, as the number of plots increases, so does the time and cost of field data collection.

Table 1. Current urban land area and percentage with completed plots within the urban park system of Phoenix, Arizona, USA (total area: 1341.48 km^2).

Typology of Green Infrastructure	Existing Green Infrastructure Land			Number of Plots Selected for Analysis
	Area (km^2)	±SE	% of Total Area	
Urban park system	194.45	±5.06	14.5%	50
City Total	1341.48		100%	

±SE = Standard error of the total.

3. Results

3.1. Urban Forest Structure of Phoenix's Park System

The forest structure of Phoenix's park system is the amount and density of plants, the types of plants present (e.g., trees, shrubs, ground cover), the diversity of species, and tree health. The urban forest of Phoenix's park system has an estimated 517,000 trees with a tree cover of 7.20%. Figure 2 illustrates the most common tree species growing in the park system. The top three species are *Vachellia farnesiana* (Sweet Acacia) (25.6%), *Parkinsonia microphylla* (Yellow Paloverde) (16.3%), and *Prosopis velutina* (Velvet Mesquite) (14.0%). The majority of trees growing within the park system had diameters less than 15.2 cm constituting 53.3% of the tree population (Figure 3). The overall tree density of the park system was 26.6 trees per ha (Table 2).

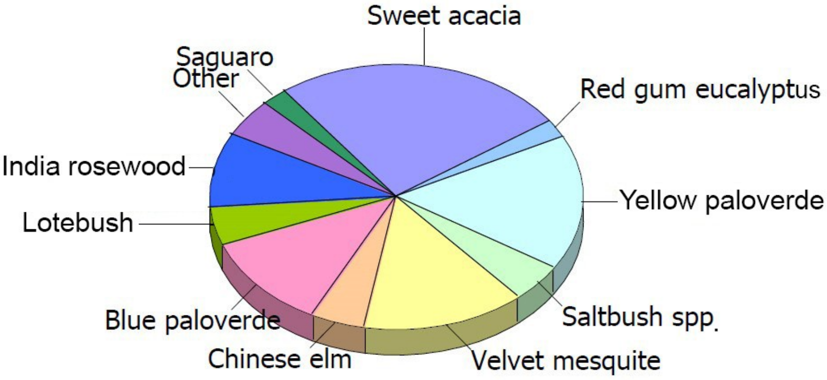

Figure 2. Tree species composition in Phoenix's urban park system.

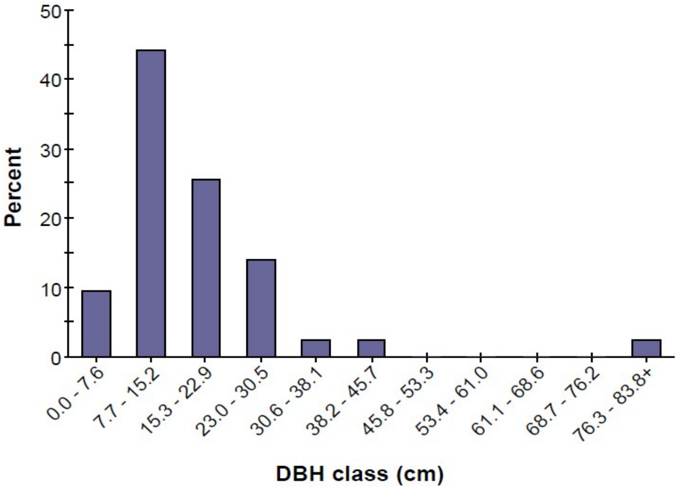

Figure 3. Percentage of tree population by diameter (DBH = stem diameter at 1.37 m above the ground line).

Table 2. Percentage tree cover and number of trees within Phoenix's urban park system.

Typology of Green Infrastructure	Area (km^2) (SE)	Percentage Tree Cover (SE)	Number of Trees (SE)	Number of Trees per ha (SE)
Urban park system	194.45	7.2 (2.68)	516,534 (197,947)	26.6 (10.18)

SE = Standard error of total.

The urban forest is composed of a mix of native and exotic tree species. Thus, Phoenix's park system has a tree diversity that is higher than surrounding native landscapes. In Phoenix's park system, about 65% of the trees are species native to North America, while 56% are native to the state or the Lower Colorado River Valley ecosystem. Species exotic to North America make up 35% of the tree population. Most exotic tree species have an origin from North & South America (14% of the species) (Figure 4). Invasive plant species are often characterized by their vigor, ability to adapt, reproductive capacity, and general lack of natural enemies. These abilities enable them to displace native plants and make them a threat to natural areas [34]. None of the 12 tree species sampled in Phoenix's park system is defined as invasive on the state invasive species list [35] (Table 3).

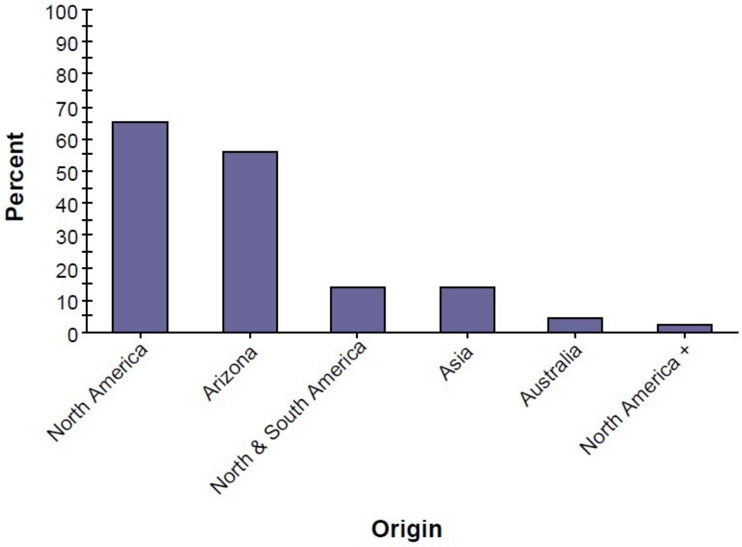

Figure 4. Percentage of live tree species by origin area growing in Phoenix's park system. The plus sign (+) indicates the plant is native to another continent other than the ones listed in the grouping.

Table 3. Urban forest in Phoenix: tree biodiversity within the urban park system.

Typology of Green Infrastructure	Number of Tree Species	Number of Native Species	Number of Non-Native Species	Number of Invasive Species
Urban park system	12	8	4	0

3.2. Urban Forest Cover and Leaf Area on Phoenix's Park System

Ecosystem services are directly proportional to the total number of trees, species, percentage of tree canopy cover and healthy leaf surface area of the plant. The amount of forest cover is a critical cooling mechanism for both its shade and its evapotranspiration. In Phoenix, the three most dominant tree species in terms of leaf area are *Vachellia farnesiana* (Sweet Acacia), *Eucalyptus camaldulensis* (Red Gum Eucalyptus), and *Ulmus parvifolia* (Chinese Elm) (Table 4). Tree canopy covers about 7.2% of Phoenix's park system. Importance values (IV) are calculated as the sum of relative leaf area and relative composition. An IV over 10 may indicate that the park system is over-reliant on a particular species for structural and functional benefits, depending on the local ecosystem [36]. Phoenix's park system has four species with an IV exceeding 10, the most important of which is Sweet Acacia with an IV of 48.5. The 10 most important species within Phoenix's park system are listed in Table 4.

Table 4. Most important species within the urban park system, Phoenix, Arizona.

Species Name	Percentage of Population	Percentage of Leaf Area	Importance Value (IV)
Sweet acacia	25.6	22.9	48.5
Yellow paloverde	16.3	12.7	29.0
Red gum eucalyptus	2.3	21.1	23.4
India rosewood	9.3	13.9	23.2
Chinese elm	4.7	14.0	18.7
Velvet mesquite	14.0	3.8	17.8
Blue paloverde	11.6	3.9	15.5
Saltbush spp.	4.7	2.4	7.1
Bottle tree	2.3	3.5	5.8
Lotebush	4.7	0.9	5.6

Estimating land cover types of the urban park system is another important element to assess ecosystem services of those parks. Bare soil (43.2%) and turf grass (26.6%) are the two most dominant permeable land cover types in Phoenix's park system (Table 5), which means that Phoenix can use its park system to strategically control and manage urban stormwater. The two impervious land cover classes (concrete/asphalt pavement and rock) make up a small percentage (15.4%) of the urban park system's total land area (Table 5). The plantable space (not covered by impervious surfaces and free of existing tree canopy cover) represents a high percentage (64.1%) of the park system, which suggests that parks have a high potential for increasing Phoenix's tree canopy cover. Phoenix has ample room to grow and expand its urban forest through its park system. As the tree canopy cover increases, this also provides other ecosystem services and benefits to local residents.

Table 5. Percentage of land cover in the urban park system, City of Phoenix, Arizona.

		Land Cover									
Typology of Green Infrastructure	**Plant Space**	**Concrete/Asphalt Pavement**	**Tar**	**Bare Soil**	**Rock**	**Herbs**	**Grass**	**Wild Grass**	**Water**	**Shrub**	**Tree**
Urban park system	64.1	9.5	1.5	43.2	5.9	2.4	26.6	4.0	0.1	6.8	7.2

Land cover totals 100% and includes pavement, tar, bare soil, rock, herbs, grass, wild grass, water, and shrub. Plant space and tree cover overlap with land cover.

3.3. *Air Pollution Removal by Phoenix's Park System*

Trees within urban park systems can help improve air quality by directly removing pollutants from the air, reducing ambient air temperature through shade and transpiration, and reducing energy consumption in buildings through shade. This reduced energy consumption also reduces waste heat and air pollutant emissions from air conditioning units and power plants. Recent updates to the air quality models are based on improved leaf area index simulations, weather and pollution processing and interpolation, and updated pollutant monetary values. As shown in Figure 5, ozone (O_3) had the greatest pollution removal value. Overall, 272 t of air pollutants (CO, NO_2, O_3, PM_{10}, and SO_2) were removed by trees within Phoenix's park system with an annual value of \$1.16 million. The urban park system is a critical component of Phoenix's green infrastructure to enhance ecosystem and human health, thus promoting better quality of life for city residents.

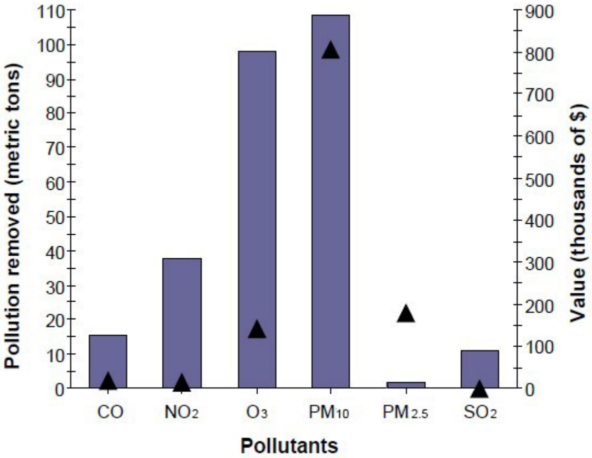

Figure 5. Pollution removal (bars) and associated value (points) for trees in Phoenix's park system. Pollution removal values were calculated based on the prices of \$1253 per metric ton (CO, carbon monoxide), \$1472 per metric ton (O_3, ozone), \$355 per metric ton (NO_2, nitrogen dioxide), \$93 per metric ton (SO_2, sulfur dioxide), \$7425 per metric ton (PM_{10}, particulate matter less than 10 microns and greater than 2.5 microns), \$105,201 per metric ton ($PM_{2.5}$, particulate matter less than 2.5 microns).

3.4. Carbon Storage and Sequestration on Phoenix's Park System

Urban forests within urban park systems can help mitigate climate change by sequestering atmospheric carbon (from carbon dioxide) in tissue and by reducing energy use in buildings, and consequently lowering carbon dioxide emissions from fossil-fuel based power [37]. The gross sequestration of trees within Phoenix's park system is about 3630 t of carbon per year (Table 6), with an associated value of $285,000. Net carbon sequestration (accounting for losses from carbon dioxide release through tree respiration) in green infrastructure is about 3380 t annually (Table 6). Trees store and sequester carbon dioxide through growth processes in their tissue. Carbon storage and carbon sequestration values are based on estimated or customized local carbon values. Carbon storage and carbon sequestration values in Phoenix are calculated based on $78 per metric ton [29].

Table 6. City total for tree effects by Phoenix's park system.

Typology of Green Infrastructure	Percentage Tree Cover (SE)	Number of Trees (SE)	Accumulated Carbon Storage (t) (SE)	Gross Carbon Sequestration (t/year) (SE)	Net Carbon Sequestration (t/year) (SE)
Urban park system	7.2 (2.68)	516,534 (197,947)	57,755.8 (31,396.3)	3633.3 (1288.4)	3383.5 (1171.1)

SE = Standard error of total.

Urban forests supported by Phoenix's park system are estimated to store 57,800 t of carbon, which is valued at $4.53 million (Figure 6). Of all the species sampled, *Eucalyptus camaldulensis* Dehnh. (Red Gum Eucalyptus) stores and sequesters the most carbon (approximately 51.9% of the total carbon stored and 24.7% of all carbon sequestered in trees growing in parks) (Figure 6).

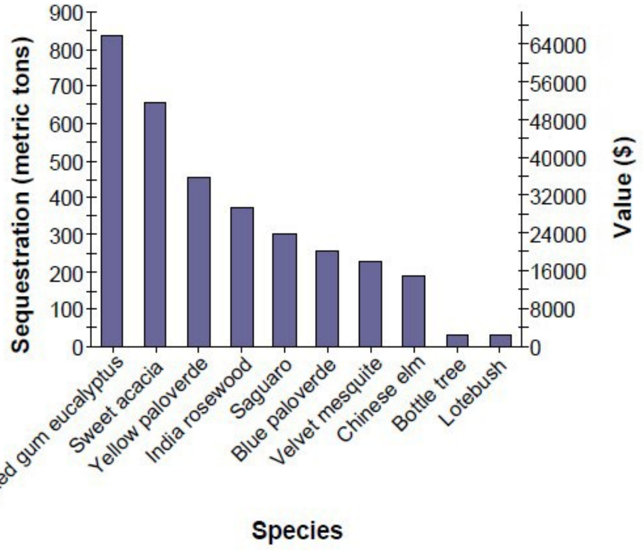

Figure 6. Carbon sequestration and value for the species with greatest overall carbon sequestration growing within Phoenix's park system.

3.5. Avoided Runoff on Phoenix's Park System

In Phoenix, the urban park system has two impervious ground cover classes (pavement and rock), which make up 15.4% of the total land cover in this category (Table 5) and has 7.2% of the tree canopy cover. The plantable space available on the urban park system is about 64.1%, which is high relative to other land covers [36]. Therefore, the urban park system has considerable additional capacity to reduce surface runoff if strategies are implemented within the system to capture stormwater in tree bioretention and infiltration beds. This suggests that Phoenix's park system could be a more valuable ecological resource that can be strategically used to increase sustainability to extreme rainfall events through urban green stormwater infrastructure that simultaneously nurtures urban forests, including trees, shrubs and pervious land cover classes. For example, urban trees within park systems are highly beneficial in reducing surface runoff. Trees intercept precipitation, while their root systems promote infiltration and storage in the soil. Currently, it's estimated that the trees growing in the City's park system help to reduce runoff by an estimated 52,800 cubic meters a year, with an associated value of $124,000, as shown in Table 7 and Figure 7 [30].

Table 7. City total for avoided runoff by Phoenix's park system.

Typology of Green Infrastructure	Number of Trees (SE)	Leaf Area Area (km^2) (SE)	Avoided Runoff (m^3/year)	Avoided Runoff Value ($)
Urban park system	516,534 (197,947)	45.8 (15.7)	52,791.65	124,120.11

SE = Standard error of total; Avoided runoff is calculated by the price $2.351/$m^3$.

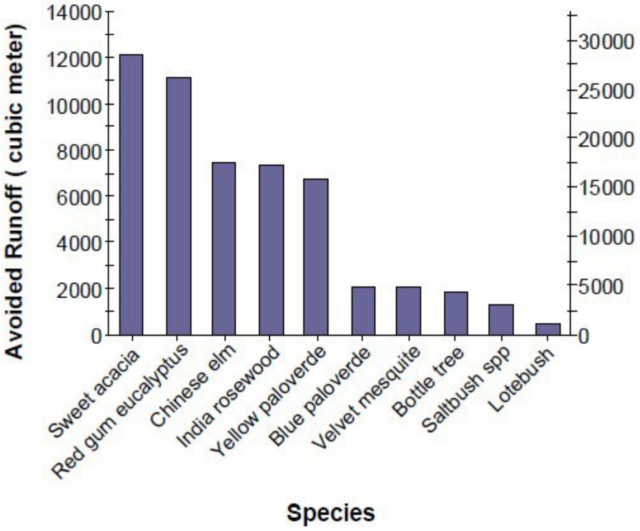

Figure 7. Avoided runoff and values for species with the greatest overall impact on runoff within Phoenix's park system.

3.6. Phoenix's Park System and Building Energy Use

Based on state-wide energy costs for Phoenix ($115.3 per MWH and $16.8 per MBTU), the trees growing within its park system were estimated to reduce energy-related costs from residential buildings by $106,000 annually. Trees also provided an additional $12,482 in value by reducing the amount of carbon released by fossil-fuel based power plants (a reduction of 159 t of carbon emissions) (Tables 8 and 9).

Table 8. Annual energy conservation and carbon avoidance due to trees within Phoenix's park system near residential buildings (note: negative numbers indicate an increased energy use or carbon emission).

	Heating	Cooling	Total
MBTU [1]	350	n/a	350
MWH [2]	29	839	868
Carbon avoided (mt [3])	8	151	159

[1] One million British Thermal Units; [2] Megawatt-hour; [3] Metric ton.

Table 9. Annual savings [1] ($) in residential energy expenditure during heating and cooling seasons (note: negative numbers indicate a cost due to increased energy use or carbon emission).

	Heating	Cooling	Total
MBTU [2]	5880	n/a	5880
MWH [3]	3344	96,737	100,080
Carbon avoided (mt)	628	25,199	28,103

[1] Based on state-wide energy costs for Phoenix: $115.3 per MWH and $16.8 per MBTU; [2] One million British Thermal Units; [3] Megawatt-hour.

3.7. Structural and Functional Values of Phoenix's Park System

The structural value of Phoenix's park system was $692 million with a carbon storage value of $4.53 million. The annual functional value of Phoenix's park system trees was over $1.5 million/year (i.e., carbon sequestration providing $285 thousand/year; air pollutants removal of $1.16 million/year; and energy saving costs combined with carbon emission reduction resulting in $118 thousand/year) (Table 10).

Table 10. City total for trees' structural and functional value by Phoenix's park system.

Typology of Green Infrastructure	Number of Trees (SE)	Carbon Storage (t) (SE)	Carbon Storage Value (US$) (SE)	Carbon Sequestration (t/year) (SE)	Carbon Removal Value (US$) (SE)	Structural Value (US$) (SE)
Urban park system	516,534 (197,947)	57,755.8 (31,396.3)	4,504,952.4 (2,448,911.4)	3633.3 (1288.4)	283,397.4 (100,495.2)	691,812,407 (270,788,843)

SE = Standard error of total.

4. Discussion

Modeling the ecosystem services of Phoenix's urban park system provides not only a picture of the current extent and condition of the system, but also provides a baseline for decision making about strategic interventions into that system that will help the city reach its Tree and Shade Master Plan goals [38]. The modeling approach is a critical first step for decision-makers to understand what ecosystem services urban park systems are currently providing in order to make decisions about how they want to change those services including the efficacy of current strategies (i.e., what is working and not working as intended). As cities implement community greening initiatives, such as Phoenix's Tree and Shade Master Plan, they can replicate the modeling approach to track changes in ecosystem services over time to ensure those initiatives enhance desirable ecosystem services, reduce disservices, and ultimately move the city toward their sustainability goals.

The total number of trees, species and percentage of tree canopy cover are very important elements in assessing the ecosystem services of urban park systems. Ecosystem services are directly proportional to the amount of healthy leaf surface area of the plant [39]. The healthy leaf surface area on individual trees growing on green infrastructure can provide more ecosystem services to citizens. Large trees provide substantially more ecosystem services, such as improving air quality and public health, cooling the air, reducing demand for air conditioning, and supporting climate change adaptation than smaller trees [40]. Trees provide critical climate-regulating ecosystem services by (1) shading surfaces and (2) through evaporative cooling. Tree's leaves reflect from 5% to as much as 30% of the incoming solar shortwave radiation [41]. This reduces the amount of radiation that can be absorbed into the pavement, buildings, and other key contributors to urban-induced heating. Short and long wave radiation play a key role in creating thermally uncomfortable conditions. Trees shield pedestrians from this radiation and provide critical microclimatic regulation of individual comfort. Although there are some large trees within Phoenix's parks (Figure 3), the much larger number of smaller trees may collectively play an important role in providing these ecosystem benefits. The trees growing within Phoenix parks with diameters less than 15.2 cm constitute 53.3% of the tree population (Figure 3), which may suggest that these are relatively young trees and thus likely to be helpful in sustaining the urban ecosystem in Phoenix for years to come. While they are small today, they have the potential to increase in size considerably over time. Alternatively, the dominance of smaller trees may be due to the frequent reliance on desert-adapted tree species including acacia, paloverde, and mesquite. Drought-tolerant native trees such as the paloverde are essentially large shrubs in their native ecosystems [42]. They are adapted to low water use and thus are seen by city officials as more sustainable and water responsible in Phoenix's hot arid climate. Yet, arid cities face key sustainability trade-offs between water conservation or more ecosystem services from larger, more water consumptive trees.

The urban forest cover of 7.2% in Phoenix's park system reduces the heating and runoff impact of impervious surfaces, such as pavement, buildings and, to a lesser degree, maintained turf grass. The 7.2% tree cover in Phoenix's parks compares to Nowak and Crane's [43] finding that Arizona cities had 11.4% urban tree cover in all urban areas. Although small, this tree cover blocks sunlight from impervious surfaces. Impervious surfaces alter the heat energy balance of the land by changing the albedo, sealing soils, and reducing moisture. Impervious surfaces reduce water infiltration and increase runoff, affecting water quality. Trees and vegetation land cover types reduce stormwater impacts by intercepting rainfall, slowing water movement, and increasing infiltration into the ground. Urban park systems hold potential as stormwater infrastructures. Many cities are developing green infrastructure as one important stormwater management strategy. Urban park system vegetative structure can cost-effectively reduce the gray stormwater infrastructure, such as retention tanks. The two most dominant land cover types in Phoenix's park system are bare soil (43.2%) and turf grass (26.6%) (Table 5). These two dominant land cover types are permeable, which means that the park system can be strategically used to control urban stormwater. Phoenix has roughly 64% of its park system available as plantable area and therefore has considerable potential to reduce surface runoff through tree planting initiatives that strategically target the park system. The urban park system is thus an essential component of a city's green infrastructure strategy and should complement other public and private green infrastructure initiatives, such as green streets, landscape ordinances, and school greening efforts as an important stormwater and climate management strategy. An urban park system is a core component of any urban green infrastructure system that can significantly improve the health and sustainability of the local urban ecosystem, providing enduring value for neighborhoods.

Climate change is an issue of global and local concern. Urban trees can help mitigate climate change and meet climate action plan goals by sequestering atmospheric carbon (from carbon dioxide) in tissue and by altering energy use in buildings, and consequently altering carbon dioxide emissions from fossil-fuel based power facilities [37]. Trees store and sequester carbon dioxide through their growth processes in their tissue. As trees grow, they accumulate carbon as wood; when they die and decay they release much of the stored carbon back to the atmosphere. Thus, carbon storage is an indication of the amount of carbon that can be lost if trees are allowed to die and decompose. This makes understanding baseline values a key part of effective long-term management of healthy forests for more holistic climate action planning. Carbon storage and carbon sequestration values are based on estimated or customized local carbon values. Carbon storage and carbon sequestration values in Phoenix are calculated based on $78 per metric ton [29]. The carbon storage in Phoenix's parks are about 57,800 t, with an associated value of $4.53 million (Table 10). Holistic climate action planning can include reuse of dead or green organic waste from urban park systems. Biomass is a renewable energy source that can either be used directly via combustion to produce heat, or indirectly after conversion to various forms of biofuel. Urban park systems are a valuable ecological resource that can be used to provide biomass energy, thus reducing the use of other non-renewable carbon-based forms of energy.

Trees within park systems affect downwind energy consumption by shading adjacent buildings, providing evaporative cooling, thus reducing building energy consumption in the subtropical desert climate with extremely hot summer months. Phoenix reduced energy consumption for residential buildings by around $106,000 annually. Trees within the park system also reduced the amount of carbon released by fossil-fuel based power plants (a reduction of 159 t), with an associated value of $12,482. Phoenix parks represent structural assets with economic value, just as other grey infrastructure in the city. This value is based on the price of replacing existing trees with other similar types of trees. In addition, they also have functional ecosystem service values (both positive and negative) based on the functions the trees perform. The structural values applied here are based on the valuation procedures laid down by the Council of Tree and Landscape Appraisers, which uses tree species, diameter, condition, and location information [22]. The number and size of healthy trees contribute to the increased structural and functional value of an urban forest. These urban forest estimates suggest that the park system offers key ecosystem benefits for city residents today and the potential future for enhancement of those benefits.

Air quality is a major problem in most cities. It can negatively affect human health, ecosystem health, and visibility. Phoenix's park system is the core component of the City's green infrastructure, removing a significant fraction of the air pollution from the city's environment. We found that Phoenix's park system may remove up to 272 tons of air pollutants (CO, NO_2, O_3, PM_{10}, and SO_2) at a value of $1.16 million/year. Air quality and utility managers can use the data to show the benefits of trees and to advocate for more funding to support tree planting and maintenance of tree species that maximize air quality benefits. Strategic tree planting in parks should consider the service provided by trees by locating them near residences to conserve energy, near parking lots to shade pavement, downwind of power plants to reduce pollution, and downwind of congested freeways to reduce vehicular VOC (volatile organic compound) pollution. When people select tree species in green infrastructures, pollutant-sensitive species should be avoided, and plantings should include the use of evergreen trees to improve tree-health and remove particulate matter year-round.

Finally, Phoenix's park system is an underutilized cooling system for many neighborhoods. In particular, many heat-vulnerable residents within the Phoenix valley depend on the cooling ability of urban forests within the City's park system. Although summer temperature in Phoenix on average exceed 37 °C over 92 times and 43 °C over 11 times annually [8], disparities in urban-heating result in dangerous heat vulnerabilities; some neighborhoods are dangerously hotter than others [6]. This exposure to heat is not only during the day, but more critically overnight when heating from urban materials triggers urban heat islands, which lead to locally elevated surface and air temperatures [44]. This exposure to heat increases residents' susceptibly to heat-related illness and death [45]. Low-income households are much more vulnerable to these health effects because the high cost of electricity prevents them from using air conditioning more consistently [46]. At the same time, heat-susceptible residents often do not have access to cooling resources such as air-conditioned cars and must traverse Phoenix's hot streets to use public transportation [6]. Phoenix's urban climate can be cooled by using the City's park system to nurture urban cool islands. Phoenix can use the ecosystem services of its park system to counteract urban heat islands to provide residents better health outcomes for the most susceptible neighborhoods. Urban park systems can improve the air quality and consequently public health, cool the air by counteracting urban heat islands, reduce the demand for air conditioning, and support climate change adaptation, all of which promote the quality of urban life [40]. The environmental benefits provided by the trees in our urban park systems are seldom recognized, but the results of this study suggest that urban park systems are a valuable ecological resource that provide multiple ecosystem services to support sustainable and healthy communities.

The findings of this research fill some important gaps in our knowledge of ecosystem service valuation of urban forests, thus improving the future design, planning and management of green infrastructure in our cities. The assessment of different types of green infrastructure is useful when considering its value in the urban landscape, while understanding an urban forest's structure, function and value can promote decision-making that improves human health and environmental quality. This research captured the current structure of Phoenix's park system as one key part of the city's larger green infrastructure network and quantified a subset of the ecosystem functions and economic values it provides to local residents. The results of this research support better planning and the management of the city's green infrastructure network, providing evidence of the valuable role trees and urban forests play in the places we live by improving the environment and enhancing both human health and the environmental quality of urban areas. The significance of this research is the new vision it provides of urban park systems as land keenly and singularly devoted to nurture more effective ecosystem services. These urban landscapes are valuable ecological resources, enhancing ecosystem health, and promoting a better quality of life for human and non-human city residents.

Findings provide useful information for urban planners, architects, landscape architects, other design professionals, advocates for healthy urban ecosystems, and others concerned with the design and planning of our urban landscape, encouraging them to treat green infrastructure as a life-sustaining resource that improves living conditions and opens up new recreational opportunities for city residents. The methodology that was applied to assess ecosystem services in this study can also be used to assess the ecosystem services provided by green infrastructure in other urban contexts and improve urban forest policies, planning, and the management of green infrastructures.

5. Conclusions

This project addresses broader concepts of sustainability and health by assessing the ecosystem services generated by an urban park system in Phoenix, Arizona. The purpose of this study is to identify and demonstrate how land dedicated to urban park systems can nurture green infrastructure that provides ecosystem services including air pollution removal values, carbon sequestration and storage, avoided runoff, structural value, and energy saving for city residents in the city's hot arid urban climate. The results of this study can be used to inform urban forest planning and management of green infrastructure in any bioclimatic region. It also promotes decision-making that will improve environmental quality and human health and well-being. This study captured the current urban forest structure of Phoenix's park system and its numerous ecosystem services and benefits to Phoenix's resident. The results of this research will support better planning and the management of the city's green infrastructure and are expected to provide data to support the inclusion of trees in the green infrastructure within existing environmental regulations, as well as providing evidence of the valuable role trees play for improving the environment and enhancing both human health and the environmental quality of urban areas.

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