Assessing Suitability of Landscape Palm Trees in the Urban Environments of Southern Arizona

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Abstract

Landscape architecture and design play a crucial role in addressing growing concerns over environmental sustainability. Palm trees (plants in the family *Aracaceae*) are an iconic and ubiquitous part of landscape design in the southwestern United States, but limited research has been conducted on the ecological and economic effects of these species. This research used a case study of the University of Arizona Campus Arboretum to examine the costs and benefits of six of the site's most ubiquitous palm species: *Brahea armata*, *Washingtonia filifera*, *Washingtonia robusta*, *Chamaerops humilis*, *Phoenix dactylifera*, and *Phoenix canariensis*. The study found the greatest net benefits from *Washingtonia robusta*, with all other species exhibiting an annual net cost for the university site. However, there is still value inherent in the use of the other palm species; beyond net economic quantitative value, consideration must also be given to additional factors pertinent to the evaluation of plant suitability when selecting plants for a site, on a case-by-case basis.

Table of Contents

Introduction

From Los Angeles to Las Vegas to southern Arizona, palm trees have come to stand as icons of the deserts of the southwestern United States. Palms exist as a symbol of the climate and overall environment of these areas, and are closely linked to images of a desert oasis. In a contemporary context, urban environments like Las Vegas or Tucson, Arizona act as these oases.

The desert climates of the southwestern US are currently experiencing a long-term drought, and the planet as a whole faces the mounting crisis of climate change (Theobald, Travis, Drummond, and Gordon, 2013). These environmental changes are likely to have lasting effects on the world's ecology, as well as the day-to-day activities carried out by humans. In response to these changes, many individuals have turned to "natural" processes, foods, and lifestyles as means of promoting sustainability and attempting to limit their individual impact on the climate. This notion can be extended to the realm of landscape architecture and design; in particular, the use of naturally occurring and regionally suitable plant materials for landscape design within urban environments.

With few exceptions, palm trees are not endemic to the southwestern United States. In other words, all but a few palms do not naturally grow in the region. Despite this, both native and non-native palm species are some of the most frequently utilized plants in contemporary landscape design in this part of the country. Taking into consideration their iconic status as geographic markers of urban oases in the southwestern US, both native and non-native palm species must be carefully evaluated for their suitability within urban built environments.

Palms comprise the botanical family *Arecaceae*, historically called *Palmate*. Many of the 2,600 known species of palms are native to Madagascar and Colombia in particular (Hodel, 2012). Yet, the trees and shrubs in the family are found across Africa, South America, Southeast Asia, as well as the southern US. While the majority of the palms that are found in present-day Arizona were introduced over the last few centuries, there are some species native to the surrounding region. Because of the environmental changes that necessitate sustainable design, this thesis aims to examine several species of non-native and native palm trees commonly found in the landscape design of Tucson, Arizona in order to assess the suitability of these plants for future sustainable development.

Palms have had a number of uses both historically and in the present, and these uses are necessary to consider when assessing the suitability of their use in contemporary landscapes. Many species produce fruit that is consumed for nourishment by humans and animals, and which is used in traditional medicine and dyes. Parts of palms are also used in modern cosmetics, furniture, baskets, and other functional products. Palms, particularly palm *trees*, provide shade for both people and animals, something which is even more valuable considering the warm and tropical climates in which they are most commonly found. Perhaps most difficult to quantify, however, is the aesthetic value of palms. And, like all photosynthetic plants, palms fix carbon, a process that is vital to mitigating global climate change. Palms contribute cultural and environmental benefits, but it is also necessary to consider their liabilities and the costs of their use when determining their suitability in this environment, especially in light of an uncertain environmental future in which natural and human resources limit the ability to maintain urban forests.

The ubiquity of the palm, both in cultural representations of the American desert and in the landscape, reflects the significant role they play in the natural and built ecosystems of the regions in which they grow. Both cultural and environmental factors are important in their own right, and each will be considered in a holistic evaluation of their future use in landscape design in the American southwest. This thesis, through an analytical case study and cost-benefit analysis, aims to determine which palm species are most suitable for landscape use in southern Arizona and the desert southwest. The research examines calculated benefits of the selected species, costs associated with maintenance and other site-related factors influencing the economic and environmental contributions of the trees as used in landscape design on the University of Arizona campus, and ultimately aims to identify palm species best suited for future use in the urban landscapes of the broader American southwest.

Literature review

Before carrying out case studies on the use of palms in the landscapes of southern Arizona, it is first necessary to understand issues of relevance to sustainable plant selection in landscape design through a thorough literature review. The aim of this section is to examine existing research in two main areas: the general role of plant selection in sustainable landscape design, and the assessment of the suitability of specific plant species through the lens of plant science. In doing so, an understanding can be developed of where each of these fields presently stands, and this understanding can be applied to the present research.

This paper aims to determine suitability of plant species based on the relative contributions of each species within a clearly defined definition of sustainability that includes environmental, social, and economic factors. The concept of sustainability as a whole is complex and challenging to define. The research group of Huang, Wu, and Yan (2015) identified a series of urban sustainability indicators "for gauging the state and progress of urban sustainability." In their examination of previous definitions for sustainability, the researchers highlight a definition provided by the United Nations Centre for Human Development (1997), which states that "a sustainable city is a city where achievements in social, economic, and physical development are made to last." The separation of sustainability into these three components is a major focus of the argument put forward by Huang, Wu, and Yan (2015). The researchers assessed several dozen indicators, of which only eight address all three aspects of the three-pronged sustainability approach (Huang, Wu, and Yan, 2015). The group concluded that additional development of urban sustainability indicators is necessary as the inclusion of all three sustainability dimensions is "important both theoretically and practically," and that normalization across these indicators would facilitate their usefulness in comparing different urban phenomena (Huang, Wu, and Yan, 2015). These indicators provide a useful context for understanding how urban sustainability is quantified, and how, in particular, economic factors can be considered in addition to environmental ones.

Pearce and Vanegas (2002) attempted to develop a framework for defining sustainability in the context of built environment systems. The framework they propose for defining sustainability emphasizes three main parameters of a given system: stakeholder satisfaction, resource base impacts, and ecosystem impacts (Pearce & Vanegas, 2002). These three are interrelated, and, in the case of landscape design, often overlap greatly in terms of resource and ecosystem impacts. Because of this, considerations of relative resource cost and benefit as well as environmental or ecosystem-related effects will be central to the present research. While considerations of stakeholder satisfaction will be utilized to an extent, it is the other two parameters that will be used to inform whether each species in this study is more or less sustainable than others.

Landscape ecology & design

Makhzoumi (2000), in the process of closely examining the ways landscape ecology can influence landscape architecture, argues that the field of landscape ecology can be used to establish scientific knowledge to “inform the design process at the local and regional levels.” In other words, research on ecological processes in the landscape can facilitate more effective design of built landscapes. Makhzoumi’s (2000) argument for the development of ecological landscape architecture and design emphasizes the sustainability impacts of designing in such a manner. Understanding the relative impacts of plant materials used in such design, as will be done in this study, will contribute to that overall ecological research.

An understanding of the use of palms in landscape design is particularly useful for establishing the case studies that will be the core of this research. Hodel (2012) examined both the biological and socioeconomic issues of managing landscape palms. The main limiting factors on palm populations in the southwestern US are "the occurrence of absolute cold.... during the late Fall to late Spring months, and, to some extent, low relative humidity" (Hodel, 2012). Because of these factors, the main species of palm that are presently used in landscape design in the desert Southwest "originate in… harsher, subtropical, or temperate climates" (Hodel, 2012). Each of the palms selected for the present research, both native and non-native, are grown commonly as landscape palms in the Sonoran Desert, and thus originate from such environments; of the non-native species, *Chamaerops humilis* is native to the Mediterranean regions of southern Europe, *Phoenix canariensis* is native to the Canary Islands in Spain, and *Phoenix dactylifera* is of unknown origin, but is believed to be native to the Middle East and north Africa (Hodel, 2012). Specifically in the context of urban forestry, Hodel (2012) argues that palms "provide more or less the same benefits and amenities as most other trees," although specific research is not cited to support this claim. Notably, however, "more [palms] must be employed to derive the same benefits and amenities on a per-tree basis," due to the relatively small canopy size of palm species, and this difference likely increases the overall water use and maintenance cost of an urban landscape compared to other plants (Hodel, 2012).

Urban forestry

Closely linked to the idea of plant materials in landscape design is that of urban forestry, defined as "management of urban trees and associated resources to sustain urban forest cover, health, and numerous socioeconomic and ecosystem services" (Nowak, Stein, Randler, Greenfield, Comas, Carr, and Alig, 2010). Researchers at the US Forest Service Northern

Research Station conducted studies on the benefits provided by landscape plants in urban forests. Nowak, *et al*. used a case study of the urban forest in Philadelphia, Pennsylvania to understand the range and extent of the positive impacts of trees in an urban environment. Specifically, analysis was done on air pollution removal, carbon sequestration and storage, and changes in building energy use, as well as several more general factors including forest risk assessment and forest structure. While the study did not focus on real estate values or other economic factors, the energy use reduction of the 2.1 million trees in Philadelphia's urban forest were valued at nearly 1.2 million dollars per year (Nowak, Hoehn, Crane, Stevens, and Walton, 2007). The research examined the effects of a very large number of specimens, but the economic impact from energy use alone indicates that urban trees are highly valuable for a municipality, and have significant impacts on reducing energy use from buildings, key to improving the environmental sustainability of a city (Nowak, *et al.,* 2007).

Urban forests are significant contributors to the social, economic, and ecological sustainability of the urban environment they occupy; a report by another group of researchers at the US Forest Service Northern Research Station examined these benefits of urban forests more broadly across the US. Their study drew from prior research across the field of urban forestry, combining quantitative and qualitative data to develop a list of general benefits including: improved air quality, water flow, noise abatement, biodiversity, real estate and business values, and overall mitigation of factors that contribute to climate change (Nowak, *et al.*, 2010). Hirokawa (2011) studied the relationship between urban forestry and sustainability in cities, highlighting the "constructed" nature of these spaces. While "tree aesthetics and symbolism have long been considerations of municipal planning," Hirokawa (2011) argues, recent interest in urban forests is driven by their environmental contributions. The study closely examines the historical context of urban forestry, rooted in tree planning programs of the City Beautiful movement, extending this context to the present-day social, ecological, and economic services of the practice (Hirokawa, 2011). While the research does not use the high degree of quantitative data presented in the studies by Nowak, *et al.* (2007, 2010), it provides a useful context for urban forestry, and how its use can contribute to a city's sustainability.

It is the specific plants that are chosen for an urban forest, however, that are one of the most significant determinants of sustainability. Hosek and Roloff (2016) conducted research on site suitability of palms through a case study of landscape palm trees in Olhão, Portugal. The researchers examined specific factors, including palm height, crown state, distance to the nearest road, and number of objects located within each plant's growing space, to determine what had the greatest effect on palm health (Hosek and Roloff, 2016). Healthy palms were assumed to have greater aesthetic value, and thus contribute greater land or economic value. Factors like distance to roads and nearby objects were found to have minimal impact on the plants' health, while plant disease and pests, which targeted certain species over others, were found to have the most significant effect (Hosek and Roloff, 2016). Because of this, the appropriateness of each plant for use in urban growing spaces was determined to be largely resultant of a given species' susceptibility to pests and disease in addition to climatic concerns (Hosek and Roloff, 2016).

Palm distribution

Eiserhardt, Svenning, Kissling, and Balsley (2011) examined the broader geographical factors that have resulted in the present distribution of palm trees. The group identified specific palm distributions across a number of scales. In particular, it was found that at the finest scales (referred to by the researchers as landscape and local scales), soil, topographical features, and, most significantly, hydrology were determinants of palm species distribution (Eiserhardt, Svenning, Kissling, and Balsley, 2011). More broadly, and similarly to the more recent research by Hodel, the researchers found that climate and water availability were the largest determinants of both palm distribution and species richness (i.e. the number of different species found in a given region) on the continental and global scales (Eiserhardt, Svenning, Kissling, and Balsley, 2011). Based on their research, it can be concluded that considerations of water systems are of great importance in determining where palm species develop. However, their research, completed in natural environments, does not take into consideration palms used in urban landscape design, and the ways human influence impacts plant development in the built environment. For example, a palm tree native to a region with high water availability could be grown in an urban environment of the dry Sonoran Desert so long as it receives sufficient irrigation.

Water use

Pittneger, Downer, Hodel, and Mochizuki (2009) examined water requirements for landscape plants, specifically focusing on palms. The group's research studied palms found in Mediterranean climates, which are quite different environments than those in southern Arizona, but included two plants that are also included in this study, namely *Chamaerops humilis* and *Washingtonia filifera*. The study investigated the impacts to "visual quality" of each plant when exposed to varied irrigation levels, finding that only two of the five subject species exhibited any increase in leaf production when under additional irrigation, while *Chamaerops humilis* and *Washingtonia filifera* exhibited no decrease in visual performance when irrigation was cut off (Pittneger, Downer, Hodel, and Mochizuki, 2009). While the Mediterranean region does generally experience greater rainfall compared to the dry Sonoran Desert, particularly in the winter months, it is useful to understand the relative resistance of these plants to negative effects from minimized irrigation. The researchers do note, however, that certain other palms, including *Phoenix dactylifera*, have significantly higher water needs than the ones examined in the study (Pittneger, Downer, Hodel, and Mochizuki, 2009).

Section conclusion

The present understanding of the environmental effects of plants in urban landscape design is fairly well developed, with a significant body of research on the role of plants in landscape ecology and design, the benefits of urban forests, the origins and present distribution of palm trees, and the necessary water use for sustaining urban forests. This paper aims to contribute to that understanding by analyzing the relative sustainability and resultant suitability of a specific family of plants in the southwestern US. As explained by Makhzoumi (2000), developments in knowledge of landscape ecology can “inform the design process” of landscape architects on a regional scale; by examining a number of factors produced by the use of both native and non-native palms in southern Arizona, landscape designers will be able to more effectively make decisions on the use of palms in urban environments.

Methodology

The intention of this thesis is to assess the suitability of palm species used as landscape ornamentals in southern Arizona. The study includes research on six palm species, three native and three non-native to the desert southwest, selected based on their frequency of use on the University of Arizona campus, mirroring their relative ubiquity in the surrounding communities. The native species are *Brahea armata* (Mexican blue fan palm), *Washingtonia robusta* (Mexican fan palm), and *Washingtonia filifera* (California fan palm), and the non-natives are *Chamaerops humilis* (Mediterranean fan palm), *Phoenix dactylifera* (true date palm), and *Phoenix canariensis* (Canary Island date palm). Photographs of each species are included in Appendix B. Because of the relative complexity involved in determining whether or not these plants are suitable, both a case study and cost-benefit analysis were utilized to develop a comprehensive understanding of palm value in urban desert landscapes.

Case study & data collection

First, a case study was conducted on the University of Arizona's Campus Arboretum, which consists of all plants at the university's main campus in Tucson, Arizona. This case study included examination of site conditions, counts and measurements of the selected palm species, and assessment of environmental and economic factors that result from the presence of the plants (for example, cost of maintenance). Measurements for each plant species included diameter at breast height (DBH). DBH is a necessary input for calculating the relative benefit of each species in the second approach of the study. Some of the factors that cannot be directly measured from the plants, including cost of maintenance, were gathered as available from the organization responsible for maintaining the landscape of the site. A qualitative ranking of the aesthetic value of each palm species was developed as well, based on the relative height and canopy size of each species, present use within the context of the site, and overall similarity to iconic palm tree imagery.

Cost-benefit analysis

The second research approach was a cost-benefit analysis using the findings of the case study. The National Tree Benefits Calculator (NTBC), an independently developed resource that takes advantage of data and calculations from the USDA Forest Service's i-Tree software suite, was used to determine the economic benefit of the trees at the study site. A breakdown of the dollar value of the benefits of each specimen, sourced from the NTBC, was used in the cost-benefit analysis. The benefits calculated by the software are storm water interception, property value impact, energy conservation, air quality impact, and carbon dioxide sequestration, which are expressed by the software in dollar values based on the monetary savings afforded by each. Also taken into consideration were costs identified during the data collection approach, including maintenance cost factors that were sourced from the Grounds Management group at the university. After the cost and benefit of each tree was calculated, the values were compared in order to determine which palms are the most beneficial (or least costly), and, crucially, to identify which palm species are most beneficial or harmful to the sustainability of the environment.

The advantage of approaching the study using this combination of a case study and a cost-benefit analysis is that values can be assigned to both quantitative and qualitative factors from the use of these plants, taking into consideration the relative value of each factor. The result of this cost-benefit analysis will be used to determine the relative suitability of each palm species for use in southern Arizona landscapes.

Results and discussion

Costs

Species name	Maintenance cost (USD)	Specimen count on site	Average cost per tree (USD)
Brahea armata	621.25	29	21.42
Washingtonia filifera	10,487.13	241	43.52
Washingtonia robusta	17,190.84	609	28.23
*Chamaerops humilis**		303	
Phoenix dactylifera	4,136.78	86	48.10
Phoenix canariensis	11,287.26	186	60.68
Total**	43,723.26	1,454	37.98
*No 2014 cost data available from UA Grounds Management for *Chamaerops humilis* **The specimen count for *C. humilis* was not used in calculating the total specimen count or total average cost per tree			

Table 1. Total palm maintenance cost for 2014, by species.

Table 1 identifies the total maintenance cost by for each species of palm for the year 2014. The dollar values include equipment and labor costs and cover all palm maintenance activity, including trimming and removal of palm skirts and fronds. This data was sourced from UA Grounds Management. The year 2014 was selected because it was the most recent year for which UA Grounds Management had complete cost data for a full year. The counts for each species were sourced from the UA Campus Arboretum. No maintenance data was available for *Chamaerops humilis* for 2014, so the specimen count of that species was not used when calculating the total average cost per tree.

Benefits

Species name	Storm water	Property value	Electricity	Air quality	Natural gas	CO_2 reduction	Total
Brahea armata	0.82	2.97	2.03	1.31	0.15	0.24	7.52
Washingtonia filifera	0.34	0.00	13.78	3.84	0.81	0.81	19.58
Washingtonia robusta	4.64	0.50	25.35	15.44	1.20	1.63	48.76
Chamaerops humilis	4.41	13.05	16.52	7.81	0.85	1.39	44.03
Phoenix dactylifera	1.42	0.83	5.45	3.40	0.36	0.34	11.46
Phoenix canariensis	4.71	0.00	24.58	15.47	1.28	1.54	47.58

Table 2. Annual monetary benefits (in USD) per tree, by species

Table 2 identifies the annual benefits, in US dollars, of an average specimen of each of the study species. The values in Table 2 are derived from the National Tree Benefit Calculator (NTBC), based on user-provided tree measurements for each species. The specific tree measurement data used is detailed in Appendix A. The climate zone used for the NTBC calculations was "Southwest Desert," based on the location of the University of Arizona Campus Arboretum. The land-use type used for the NTBC calculations was "Industrial or large commercial business." Certain parts of the UA campus may be better classified as "Multi-family residential," but the results output from using each of the two land-use types was very similar, so "Industrial or large commercial business" was used in all cases. The NTBC does not have unique data for the species *Washingtonia robusta*, so the category "Other, Palm Evergreen Large" was used to calculate benefits for that species.

The benefits are broken down into six categories, as defined by the National Tree Benefit Calculator. All of the benefit categories were assigned a dollar value in USD by the NTBC, even in cases where the metric is not measured in dollars, allowing for direct comparisons across species.

The first category is storm water, or the amount, in gallons, of storm water runoff that will be intercepted by the tree over the course of a year. *Washingtonia robusta* was calculated to have the highest runoff interception of the three native species; however, two of the non-native species were calculated to intercept similarly high volumes of storm water.

The second category is property value, or by how many dollars nearby property values will increase from the presence of the tree annually. The model used by the NTBC calculates this value by using the total leaf surface area of the tree, in conjunction with factors specific to each species, including seasonal changes. The species *Washingtonia filifera* and *Phoenix canariensis* each was calculated to create a property value increase of zero dollars, despite the relatively large size of the trees and their high leaf surface areas.

The third category is electricity, and is measured in annual kilowatt-hours conserved by cooling caused by the presence of the tree. This metric is calculated based on shading, evapotranspiration, and wind interception from the tree, and is used to calculate a dollar value for this category. *Washingtonia robusta*, a native species, was calculated to produce the greatest electricity savings, but *Phoenix canariensis* had similarly high savings; both of these species have large canopies, and *Washingtonia robusta* grows to be very tall relative to some of the other palm species, meaning it is able to shade buildings effectively.

The fourth category, natural gas, is based on the same calculations as the third, but refers specifically to the reduction of oil or natural gas consumption, and is measured in therms per year. The output dollar values in this category are relatively low compared to most of the other categories, with most species calculated to have a natural gas reduction valued at around 1 USD. *Brahea armata* and *Phoenix dactylifera* notably have even lower values in this category, consistent with their calculated benefits in most other categories.

The fifth category is air quality, or the amount of certain pollutants that is avoided, absorbed, or intercepted by the tree. These air quality benefits are quantified in dollars and broken down by ozone, nitrogen dioxide, sulfur dioxide, PM10 (certain other particulate matter), and other volatile organic compounds. The native and non-native species indicated similar benefits in this category, with the greatest benefits provided by *Washingtonia robusta* and *Phoenix canariensis*, two of the largest species.

The sixth category is CO_2 reduction, or the amount of atmospheric carbon dioxide removed by the tree. The calculation for this category factors in two sources of carbon dioxide reduction provided by trees: carbon sequestration, or the amount of CO_2 processed by the plant naturally, and the amount of CO_2 emissions avoided by the reduced heating and air conditioning demands afforded by a plant's proximity to a building. The non-native species generally reduced a greater amount of CO_2 than the native species, but *Washingtonia robusta* was calculated to have the CO_2 reduction with the greatest value.

Aesthetic value

Species name	Ranking
Washingtonia filifera	1
Washingtonia robusta	2
Phoenix canariensis	3
Brahea armata	4
Chamaerops humilis	5
Phoenix dactylifera	6

Table 3. Ranking of aesthetic value of each palm species

A qualitative ranking, reflected in Table 3, for the aesthetic value for each palm species was developed subjectively, based on the present use of the species on the Campus Arboretum site, as well as the visual similarity of the species to iconic images of palms, which is tied closely to taller, single-trunk species. Because of these criteria, *Washingtonia filifera* was ranked most highly for aesthetic value. This species is used in the landscape design of many prominent areas of the site, including along the main entry from University Boulevard, as well as along the campus mall. This species also closely corresponds with iconic images of palms, as is the case with the visually-similar *Washingtonia robusta*, which is used along other major thoroughfares within the site. *Phoenix canariensis* is also similar to iconic palm imagery, yet it is used to a much more limited extent on the Arboretum site. *Brahea armata* ranked somewhat lower despite its relative height, due to its sparse use on campus and the shape of its leaves, which is less conventional than some of the other species. The two lowest-ranked species, *Chamaerops humilis* and *Phoenix dactylifera*, both frequently grow with multiple narrow trunks, and are fairly short species. However, *Chamaerops humilis* is used very frequently within the site, including a long line of specimens along the eastern end of the campus. *Phoenix dactylifera* is used infrequently, and has longer, less traditional palm leaves than the other species, resulting in being ranked lowest for aesthetic value.

The aesthetic value of these species are economically beneficial to the site, because, as a college campus, perceived attractiveness can influence recruiting of prospective students and generate resultant income for the university. However, it is difficult to quantify the economic benefit of each species, or of palm trees as a whole, from their visual appeal. Because of this, aesthetic value cannot be used in the net value cost-benefit calculations, but can be used when considering the relative benefit of the presence of each species within the site.

Net value

Species name	Annual benefit per tree (USD)	Annual cost per tree (USD)	Net annual benefit per tree (USD)	Net annual benefit for entire site (USD)
Brahea armata	7.52	21.42	-13.90	-403.10
Washingtonia filifera	19.58	43.52	-23.94	-5,769.54
Washingtonia robusta	48.76	28.23	20.53	12,502.77
*Chamaerops humilis**	44.03		44.03*	13,341.09*
Phoenix dactylifera	11.46	48.10	-36.64	-3,151.04
Phoenix canariensis	47.58	60.68	-13.10	-2,436.60
*No 2014 cost data available from UA Grounds Management for *Chamaerops humilis*; net benefit values do not include any costs for this species				

Table 4. Net annual monetary benefit per tree and for entire site, by species

Table 4 includes the total costs and benefits per tree for each species, as well as the net value derived from these costs and benefits, both per tree and extrapolated to the entire site by multiplying the value by the total number of specimens present. The only palm species calculated to have an annual net monetary benefit per tree was *Washingtonia robusta*. Despite a positive final net benefit listed in Table 4, a lack of annual cost data means it is not possible to assess the actual net value for *Chamaerops humilis*; the positive value listed is not indicative of known annual net savings or costs. The remaining species all were calculated to have an annual net cost, with the species *Phoenix canariensis* and *Brahea armata* being the least costly. *Washingtonia filifera* and *Phoenix dactylifera* were calculated to be the most costly, with the latter accruing a cost of over 35 USD each year, higher than the annual net benefit per tree for *Washingtonia robusta*. Without including the incomplete results for *Chamaerops humilis*, the native species have a generally more positive net value than the non-native species, although the non-native palm *Phoenix canariensis* has the highest annual net value after *Washingtonia robusta*.

Applying these net values to the total number of trees of each species across the entire site, the native species generally had a greater net value than the two calculable exotic species. The native species *Washingtonia filifera*, however, was calculated to have the greatest annual cost due to the high number of specimens present on the Campus Arboretum. Comparatively, the total net value of all specimens of the native species is greater than the total value of all specimens of the two non-native species.

Taking into account the aesthetic value rankings, it is more difficult to establish a clear value difference between the native and non-native species. While the native species *Washingtonia filifera* and *Washingtonia robusta* were subjectively ranked most highly for aesthetic value, the exotic species *Phoenix canariensis* was ranked highly as well. *Washingtonia robusta*'s high placement on the aesthetic value ranking reinforces the overall high net value of that species; conversely, the aesthetically highest-ranked palm species, *Washingtonia filifera*, is also the most monetarily costly, making it difficult to assess its overall value. Based on both aesthetic and monetary value, a clear difference between the use of native and non-native palm tree species cannot be established. However, the Mexican fan palm, *Washingtonia robusta*, is the most beneficial of the studied species in both subjective aesthetic value and economic benefit for the study site. For this reason, the use of this palm species is highly suited to use within a university campus in the Sonoran Desert region.

Conclusion

Based on the findings from this research, the Mexican fan palm, *Washingtonia robusta,* is the most economically beneficial and one of the most aesthetically valuable of the palm species assessed in this research. Each of the other species for which complete data was available had an annual net cost, due to high annual maintenance costs and comparatively low monetary benefits. However, several of these net-cost palms, particularly *Washingtonia filifera*, were assessed to have particularly high aesthetic value. While most palms exhibited a net cost after taking maintenance into account, each tree species included in this research was calculated to have a significant degree of economic benefits across several categories. Beyond the calculated economic value, these benefits, including energy use reduction and CO_2 sequestration, contribute to the ecological and environmental sustainability of the urban system they occupy, which can be beneficial on a broader spatial scale and in the long term.

While attempts were made to determine whether native or exotic plants were more suitable to the site, the findings indicated that a greater deal of complexity is involved in prescribing a broad category of plants for landscape design over another. In general, native plants were calculated to have higher net values; however, the use of both native and non-native plants on the site contributes aesthetic value that is not accounted for by the economic calculations alone. Similarly, despite the strong difference between the net value of the Mexican fan palm and the other palm species, prescribing the use of a single species for a site as large as the Campus Arboretum is difficult. Because of the complexity inherent in selecting plant materials for use in landscape design, there are a great number of factors that must be taken into consideration beyond maintenance costs and the six primary monetary benefits included in this research. A plant's site-specificity and role within a landscape's broader composition and physical context, considerations for microclimates within a site, in addition to considerations for economic factors all must be taken into account when selecting plant materials for a site. If these complexities were to be ignored, replacing all palm trees on the site with *Washingtonia robusta* specimens would be the most economically viable option, but the visual variety and other benefits provided by the five other frequently-used palm species would be lost. On a site with different conditions than those of the Campus Arboretum, with a different overall land use, different maintenance practices and infrastructure, and different existing landscape design and plant composition, an entirely different palm species may be preferable to the one found ideal in this research.

While it is clear that effectively maintaining palms can be more costly than beneficial, the iconic nature of palm trees in the Sonoran Desert and surrounding regions mean that their ubiquitous use in landscape design is likely to continue into the future. Awareness of the costs associated with the use of one palm species over another, with considerations for site conditions on a case-by-case basis, can help facilitate more effective and cost-effective landscape design, and, if done carefully, may lead to a more economically and environmentally sustainable future.

Limitations

The first major limitation faced during this research was that of data availability. Initially, three case studies were planned, including a residential site and a commercial site in addition to the Campus Arboretum. However, acquiring maintenance cost data with a degree of granularity comparable to that of the data provided by UA Grounds Management for the Campus Arboretum site was not possible for the initially-selected residential and commercial sites, so case studies of a similar scale on those other land use types could not be conducted. Future research on the use of palm trees in landscape design could benefit from examining the costs and benefits of palm species across a number of land uses, in order to better understand the suitability of each species across different kinds of urban landscape.

Data availability was also an issue within the UA Campus Arboretum case study: only one year (2014) had complete maintenance data available, and there were no records of maintenance done on specimens of the species *Chamaerops humilis* during that year, despite its very high frequency of use throughout the site. This significantly affected the final assessment of that species' net value, although the decision was made to include the species in the overall analysis in spite of the missing cost data for that palm. While the data used was highly detailed and complete in other regards, future research could benefit from complete cost data on all studied species. Similar future research could also benefit from examining a greater number of palm species in total, as certain other sites may frequently use palm species that were not selected for this research. Water use data was also not available; the amount of water that is needed to irrigate and maintain a given plant specimen is difficult to quantify and is not presently recorded by UA Grounds Management. Future research that independently collects data on irrigation water use for individual plants would be useful in better understanding the full cost of using certain species in urban landscapes.

Limitations also arose from the National Tree Benefits Calculator (NTBC) used for calculating the monetary benefits for each species across six categories. This software only allows for calculations to be done on a single plant at a time, meaning the software is not able to account for any interactions that may occur between multiple plants in a given area. Diminishing returns on the benefits contributed by a plant may occur when it is located in close proximity to other plants, and applying the NTBC's calculated benefits for a single tree to a large number of trees across the entire site may not be accurate because of this. The NTBC also does not account for the distance of a tree from the nearest building, which impacts certain of the benefits the software aims to calculate, including property value and shading-related energy reduction. Instead, the software assumes a standard distance for each tree, which does not reflect actual site conditions. The use of more advanced software that is able to account for additional complexities like these would allow for results that are more accurate to the actual state of the site, and the impact that each tree contributes. The NTBC software output values of 0 USD for the property values benefit category for two of the six species included in this study; this likely does not reflect the actual benefit provided by those species for property value, and may have been a limitation of the software's ability to properly calculate the benefits provided by those species. This may have impacted the results of the research as a whole, and using more consistent software for future research would be beneficial as well.

There are a number of opportunities for future research to expand on this study. In addition to the use of more complete data and more nuanced tree evaluation software, the use of other methods could improve the quality of results in a similar study. The method used to rank the aesthetic value of palm species was highly subjective, and a method based on quantitative data related to palm health and other factors may be more effective for assessing palm tree suitability and benefits. The inclusion of a wider range of palm species and land use types would also improve the usefulness of research similar to this study.

Appendices

Appendix A - Palm measurement data

Species name	Average circumference at breast height (inches)	Average diameter at breast height (inches)
Brahea armata	58	18.47
Washingtonia filifera	82.75	26.35
Washingtonia robusta	46	14.65
Chamaerops humilis	47	14.97
Phoenix dactylifera	108	34.39
Phoenix canariensis	81.5	25.96

Table 5. Measurements of circumference and diameter at breast height, by species

Circumference measurements were taken on select palms at the University of Arizona Campus Arboretum for each species, at 4.5 feet above the ground (breast height). The circumference was averaged for the measured specimens within each species, and diameter at breast height (DBH) was calculated based on the averaged circumference. The calculated DBH was used in the National Tree Benefits Calculator for determining the benefit provided by each specimen of each species on the site.

Appendix B – Palm species photos

Figure 1. ***Brahea armata*****, Mexican blue fan palm (Photo from UA Campus Arboretum)**

Figure 2. ***Washingtonia filifera*****, California fan palm (Photo from UA Campus Arboretum)**

Figure 3. ***Washingtonia robusta*****, Mexican fan palm (Photo from UA Campus Arboretum)**

Figure 4. ***Chamaerops humilis*****, Mediterranean fan palm (Photo from UA Campus Arboretum)**

Figure 5. ***Phoenix dactylifera*****, True date palm (Photo from UA Campus Arboretum)**

Figure 6. ***Phoenix canariensis*****, Canary Island date palm (Photo from UA Campus Arboretum)**

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Reflection

Working on this capstone in fulfillment of the Sustainable Built Environments degree has been a valuable part of my education, and has allowed me to put into practice the research skills I have developed over the course of my time in the program. The capstone allowed me to expand my understanding of the built environment, particularly in terms of the role of plant selection and sustainable design considerations within urban landscape development. While I do not plan to immediately pursue a post-graduate degree or career in landscape architecture, this project has allowed me to explore and deepen my interest in that field, and will also serve as valuable experience when seeking a career related to urban planning. Beyond the development of research and writing skills, this capstone has given me the opportunity to develop my professional communication and independent decision-making skills throughout the data collection and interpretation processes, which will also prove invaluable in the future of my career.