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Evaluating Structural and Temporal Factors Affecting Supply of Ecosystem Benefits in a University Urban Environment in South Carolina, USA

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Abstract

Sustainable urban forest management is still an evolving concept, particularly as it pertains to a sustainable supply of ecosystem benefits and management planning. Urban forestry maintains a greater human dimension component than traditional timber-oriented rural forestry because urban trees grow in city centers and neighborhoods, supplying critical ecosystem benefits to the population centers. The overall goal of this study was to evaluate the relationship of urban forest stand structure and its temporal dynamics with the sustainable supply of ecosystem benefits in university environments. Individual tree data were collected from a completed inventory, while the i-Tree Eco model was used to generate ecosystem benefits data from the Clemson urban forest. The cumulative-benefits supply curve had an inverted J-shaped curve, but the average supply curve had a negative slope against the species richness. Likewise, individual tree variables total height, DBH, leaf area, and crown height strongly correlated with the total ecosystem services supply. Based on the temporal supply trends, the study area trees were broadly segmented into three groups: establishment, growth, and legacy, with 65%, 31%, and 4% frequency distribution, respectively. Urban forest managers need to identify forest management goals and preferred ecosystem benefits among the urban communities to guide the required forest structure and dynamics to ensure a sustainable and functioning urban forest.

Keywords

Sustainability, Urban Forest Structure, Ecosystem Services, i-Tree, Economic Benefits

1. Introduction

Sustainable urban forest management is still an evolving concept, particularly concerning climate change resiliency and ecosystem services. Urban forests come in various structures and sizes, including urban parks, street trees, greenways, river corridors, gardens, and wetlands (Nowak & Dwyer, 2007). An urban natural ecosystem, a dynamic human-environment system, requires special attention to ensure that urban planning would produce sustainable urban forest outputs in the continuum (Dwyer et al., 1992). A traditional approach to tree species selection for urban plantations, *the right tree at the right location*, puts extra emphasis on site suitability while giving relatively less consideration to the potential supply of ecosystem benefits in the future after those trees get established. Urban trees could serve as a natural solution to drainage and water quality, reduce air pollution, and offset carbon dioxide emissions (Escobedo et al., 2006; Nowak & Crane, 2002). Demand for these ecosystem services from urban natural environments has been increasing due to large-scale construction and land use activities in major urban centers worldwide (Peng et al., 2020; Purcell et al., 2020). Along with numerous socio-ecological benefits, urban forestry-based businesses and activities support thousands of jobs contributing substantially to the local and regional economies (Parajuli et al., 2022).

Four-fifths of Americans currently reside in urban areas (USCB, 2021). Escalating urbanization has led to increasing demand for ecosystem benefits, and the trend could be expected to further increase in the future (Nowak & Greenfield, 2018). Sustainable urban forest management has become an essential component of overall city planning now, which requires a value-based understanding of trees before large and well-established trees are considered before being removed. Sometimes, well-functioning trees that continue to provide multiple ecosystem benefits might be removed due to a lack of knowledge concerning urban forests' inherent values, as they might be considered a public nuisance (Joshi et al., 2015). Equally, urban environments put tremendous stress on tree growth due to the grey infrastructure of streets, sidewalks, curbs, buried utilities, overhead power lines, and buildings. Trees could become structural assets, an essential component of the green infrastructure, that grow in value over time with proper care. Still, their value could quickly decline and eventually become a liability to communities without care. Growing healthy and functional trees requires advanced planning that emphasizes their long-life span and maintenance requirements (Dwyer et al., 1992, Callaghan et al., 2019a). Hauer & Peterson (2016) found that lack of planning and timely maintenance made some municipalities in the U.S. allocate more budget to tree removal than planting activities. A municipal census of urban tree activities found that 67% of urban communities had conducted tree inventories, but only 25% had set canopy percentage goals to schedule their tree planting, tree removal, and pruning activities in the United States (Hauer & Peterson, 2016).

Using the urban tree growth and ecosystem services model, it has become possible to quantify urban ecosystem benefits with reasonable statistical validity (Livesley et al., 2016; McPherson et al., 2005). Multiple softwares are available for urban tree inventory and ecosystem services estimation, but the i-Tree suite (Eco, Landscape, Design, Canopy, and Planting) has been getting increasing popularity in academia because it is a peer-reviewed and publicly available tool developed and constantly maintained by the U.S. Forest Service (McPherson, 2007). Among other options within the i-Tree suite, Eco is a more versatile tool to quantify and predict ecosystem benefits from trees located in parks, neighborhoods, or municipal forests using the inventory data (Bassett, 2015; Martin et al., 2011; McPherson et al., 2005; Roy et al., 2012). One of the unique functionalities of Eco is its ability to do predictive and scenario modeling for tree planting campaigns, invasive species, or weather-induced mortalities.

Recent urban forestry studies on ecosystem benefits have primarily focused on estimating tree number and species diversity impact on ecosystem benefits supply (Hulvey et al., 2013; Martin et al., 2011; Ross et al., 2020; Subburayalu & Sydnor, 2012). In general, urban tree economics studies have emphasized tree numbers or species types available with less emphasis on the forest as a dynamic ecosystem, where overall forest structure and its growth pattern would be crucial for sustainable supply of ecosystem benefits to urban communities over time. Vogt et al. (2015) reviewed urban forest benefits and management costs to generate a hypothetical inverted U-shaped curve for ecosystem benefits, but the cost curve was U-shaped, with mature trees providing maximum benefits and tree maintenance costs increasing rapidly for the older trees. These benefit and cost curves have yet to be tested with empirical data from the urban environments. Further empirical studies focusing on temporal dynamics of ecosystem services supply trends would highlight how urban forest managers could maintain efficiency and effectiveness in using limited resources while planning an optimal supply of benefits in ever-expanding urban neighborhoods.

Urban forestry maintains a greater human dimension component than traditional timber-oriented rural forestry because urban trees grow in city centers and neighborhoods, supplying critical ecosystem benefits to the population centers. Urban forest sustainability is often described in terms of species diversity, and urban forest certification standards have recently been proposed to evaluate it in operational contexts. However, in classical forestry, Q-factor determines the number of trees in each diameter class that helps achieve a J-shaped diameter distribution curve for sustainable uneven forest management (Khanal & Straka, 2020a). The Q-factor could be a more easily measurable tool to evaluate a target diameter distribution in urban communities, but setting a target canopy cover has been common among municipalities in the United States. Sustainable Forestry Initiative (SFI) has recently developed a sustainable urban forest management standard for urban forest certification in the U.S. (Kadam & Dwivedi, 2021). An ideal optimal diversity to increase forest resiliency and its correlation with the supply of multiple ecosystem benefits is still a subjective concept in urban forestry. Hulvey et al. (2013) conducted a simulation study of tree diversity vs. monoculture plantation's impact on carbon sequestration and concluded that mixed plantings result in more carbon storage. Likewise, Ross et al. (2020) found leaf area and tree diameter strongly correlated with the supply of ecosystem benefits, avoided run-off and water interception, but the species count was negatively correlated with rainfall interception. A rule-of-thumb diversity index, 10% - 20% - 30% for species, genus, and family, has been a common operational guide for maintaining the abundance and evenness of species in city environments (Subburayalu & Sydnor, 2012).

Incorporating social and ecosystem services supply considerations in sustainable urban planning is highly important. Even though the public generally recognizes some benefits of urban trees, educational programs on the economic and environmental values of trees are necessary to justify spending additional tax dollars or increasing storm and water utility bills to protect and maintain urban forests (Hauer & Peterson, 2016). Understanding and communicating an urban forest's structure, function, and value can promote management decisions that improve human health, environmental quality, and even local economies by increasing property values and aesthetics in urban communities (McPherson, 2007). Likewise, public decision-makers must also understand how urban forest structure is associated with ecosystem benefits for allocating limited city resources in sustainable urban forest planning (Callaghan et al., 2019b; Khanal & Straka, 2020b).

The overall goal of this study was to evaluate the relationship of urban forest structure with the supply of ecosystem benefits in a university environment. Based on the tree information estimated from the i-Tree Eco, we examined the composition of urban forests and their inherent ecosystem services, identified the major factors associated with the supply of ecosystem services, and assessed the temporal dynamics of urban forests in a complex human-urban tree interaction.

2. Materials and Methods

2.1. Materials

Data Collection

The study data were collected from the Clemson University urban forest located in Clemson, South Carolina, United States. Clemson University is a public university with over 25,000 students and an urban forest covering over 500 Hectare (34.6834˚N, 82.8374˚W) in the foothills of the Blue Ridge Mountains in the southern United States. Tree data were collected from a complete inventory of trees located within the university property. Individual tree measurements include species, diameter, height, and position locations for all the trees. These tree data get regularly updated using an online system to keep tree removal or new plantings on record. Then, the tree inventory data was formatted for the i-Tree Eco 6.2 analysis. The i-Tree Eco is a peer-reviewed and publicly available software by the USDA Forest Service (https://www.itreetools.org/). The i-Tree Eco Model uses local pollution data and tree inventory records to provide urban trees' structural and functional benefits in a given location. In this study, the nearest weather station (Oconee County, South Carolina, USA) data from 2016 were used for pollution-related information. Leaf area index and crown height were estimated for each tree using species-specific equations within the Eco Model.

2.2. Methods

2.2.1. Ecosystem Services Analysis

The i-Tree Eco Model (i-Tree, 2022) is an ecosystem services valuation tool that integrates various assumptions and urban tree growth models to estimate ecosystem benefits using site-specific data provided by the user. The model used hourly weather data from the nearby local weather stations after its geo-location was provided. Estimating average and cumulative ecosystem benefits against species richness needed the total value of the individual ecosystem benefits (carbon, run-off removal, and pollution reduction). Species richness, a standard measure of species diversity, indicates different species present in the study area (Hulvey et al., 2013). Similar to our study, Hulvey et al. (2013) evaluated how species richness affects carbon storage in urban trees. The average supply of ecosystem benefits under various tree diameter classes was estimated for all species types, using tree diameter (DBH for the larger trees) as a proxy variable for the age or time. Tree stem diameter has been previously used as a proxy variable for age or temporal dimension in forestry studies (O'Brien et al., 1995; Trouillier et al., 2019).

2.2.2. Statistical Analysis

Pearson's correlation analysis was conducted to evaluate the strength of linear association between tree measurements (diameter, height, leaf area, and crown height) and the ecosystem services (pollution removal, avoided run-off, and carbon sequestration). Pearson's correlation coefficient ranges between −1 and +1, where +1 indicates a perfect positive correlation meaning that for every unit increase in one variable, there will be a positive increase in the other variable. Ross et al. (2020) also conducted a similar statistical analysis to evaluate the influence of tree attributes on environmental effects. All statistical analyses were performed using SAS 9.4 version.

3. Results

3.1. Species Composition and Ecosystem Services Supply

There were only thirteen tree species with over 100 trees. Their ecosystem benefits supply rate varied between \$0.88/tree/year to \$11.66/tree/year. Ranking the most frequent species based on their average ecosystem services supply ($/tree/year) versus their availability in terms of frequency resulted in two different ranking orders. As depicted in **Table 1**, Common crape myrtle was the most common species (12.82%), but Willow oak (9.04%), Water oak (1.80%), and River birch (2.22%) supplied more ecosystem benefits, on average, per tree every year. Likewise, average ecosystem benefits ($/tree) varied for different species types. On average, River birch provided the highest carbon sequestration benefits ($5.42/year), while Willow oak was the best performing species in terms of air pollution removal ($2.21/year) and stormwater ($5.19/year) benefits. Only the top seven species could supply benefits at a greater than average rate ($4.08/tree) for the overall forest.

Clemson urban forest supplied ecosystem benefits about $31,000/year, but the supply curve had an inverted J-shape against species richness, with an increasing rate at the beginning but almost a flat line after a few species (**Figure 1**). The average benefits rate varied between $12/year to $4.80/year against increasing species richness in the forest. After a sharp decline with species richness from $12/species to $5.23/species for the first seven species, the average benefits curve remained almost flat for the remaining species. The first seven species supplied more benefits (about $22,000/year cumulative, or 71% of the total supply) than the remaining species in the study area forest.

Table 1. Ecosystem benefits (CO_2, air quality, stormwater, and total) by species types for the most common species in the Clemson urban forest.

Species	%	CO_2, $/year	Air quality, $/year	Stormwater, $/year	Average, $/tree (SE)	Rank
Crape myrtle (Lagerstroemia indica)	12.82	0.67	0.14	0.07	0.88 (±0.47)	13
Willow oak (*Quercus phellos*)	9.04	4.25	2.21	5.19	11.66 (±8.42)	1
Red maple (*Acer rubrum*)	6.80	4.34	0.79	1.86	7.00 (±5.73)	5
White oak (*Quercus alba*)	6.51	2.82	1.47	3.45	7.75 (±6.68)	4
American holly (*Ilex opaca*)	6.14	0.49	0.31	0.73	1.54 (±1.65)	12
Loblolly pine (*Pinus taeda*)	5.85	1.91	0.43	1.00	3.35 (±3.12)	9
Flowering(pink) dogwood (*Cornus florida*)	4.76	1.29	0.08	0.21	1.58 (±1.23)	11
Foster's (Topal) holly (*Ilex attenuata*)	3.73	1.78	0.15	0.35	2.27 (±1.57)	10
Chinese elm (*Ulmus parvifolia*)	2.95	3.79	0.59	1.38	5.77 (±2.30)	6
Sugar maple (*Acer saccharum*)	2.87	2.88	0.95	2.23	6.07 (±4.15)	7
Southern magnolia (*Magnolia grandiflora*)	2.28	2.63	0.75	1.77	5.16 (±4.88)	8
River birch *(Betula nigra*)	2.22	5.58	1.16	2.72	9.46 (±4.50)	3
Water oak (*Quercus nigra)*	1.80	5.42	1.54	3.62	10.59 (±3.87)	2
Total benefits (cumulative)		$14,249.15	$4,665.16	$10,924.16	$29,835.89	

**Overall average benefit was $4.08/tree with an average diameter of 10.67 cm and height of 4.08 m for the 125 species types.

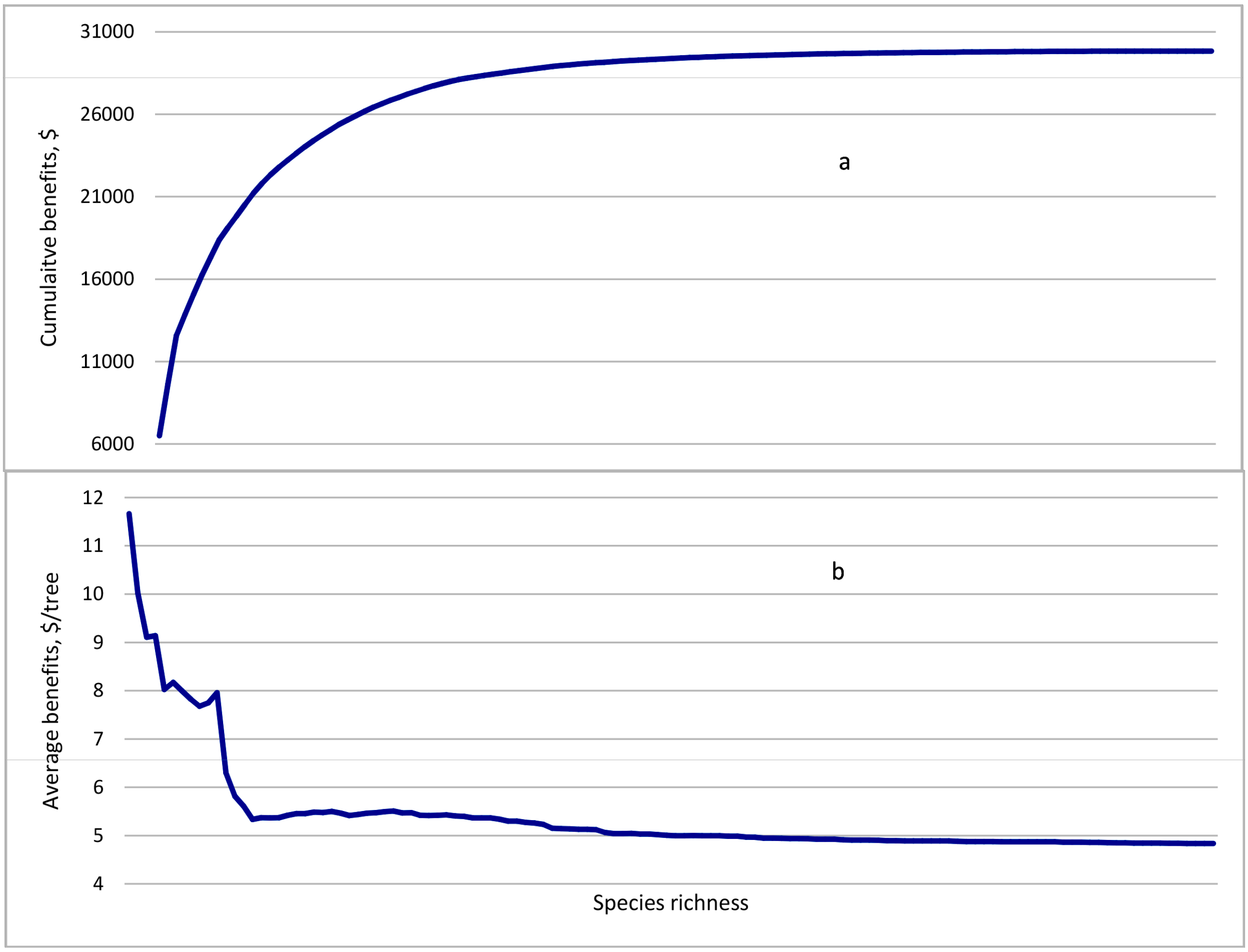

Figure 1. Relationship of species richness with (a) cumulative ($) and (b) average ($/tree) ecosystem benefits in Clemson urban forest.

3.2. Tree Attributes Affecting Ecosystem Services Supply

Individual tree's structural parameters, diameter, height, leaf area, and crown height were strongly correlated ($\rho > 0.69$, $P < 0.00$) with the three ecosystem benefits evaluated in the study (**Table 2**). Tree parameter leaf area was perfectly correlated with avoided run-off and air pollution removal. Tree diameter was strongly correlated ($\rho > 0.88$, $P < 0.00$) with all three ecosystem benefits. Tree crown height was also strongly correlated ($\rho > 0.87$, $P < 0.00$) with avoided run-off and pollution removal than carbon sequestration rate. Avoided run-off and air removal benefits had similar correlation coefficients for the four tree parameters.

3.3. Temporal Dynamics of Urban Forests and Ecosystem Services Supply

The average supply of ecosystem services ($/year) maintained a nearly linear trend until it reached about a $20/year benefits rate; after that, it had a wider variation for the older or legacy trees (**Figure 2**). The annual benefits supply

Table 2. Pearson's correlation coefficient between structural parameters (diameter, height, leaf area, and crown height) and ecosystem benefits (run-off benefits, carbon sequestration, and pollution reduction) in the Clemson urban forest.

	Avoided run-off	DBH	Height	Leaf Area
Avoided run-off	-			
DBH	0.88 (<0.00)	-		
HT	0.78 (<0.00)	0.85 (<0.00)	-	
Leaf area	1.00 (<0.00)	0.88 (<0.00)	0.78 (<0.00)	-
Crown height	0.87 (<0.00)	0.89 (<0.00)	0.78 (<0.00)	0.87 (<0.00)
	Carbon storage			
Carbon storage	-			
DBH	0.89 (<0.00)	-		
HT	0.70 (<0.00)	0.85 (<0.00)	-	
Leaf Area	0.82 (<0.00)	0.88 (<0.00)	0.78 (<0.00)	-
Crown Height	0.69 (<0.00)	0.89 (<0.00)	0.78 (<0.00)	0.87 (<0.00)

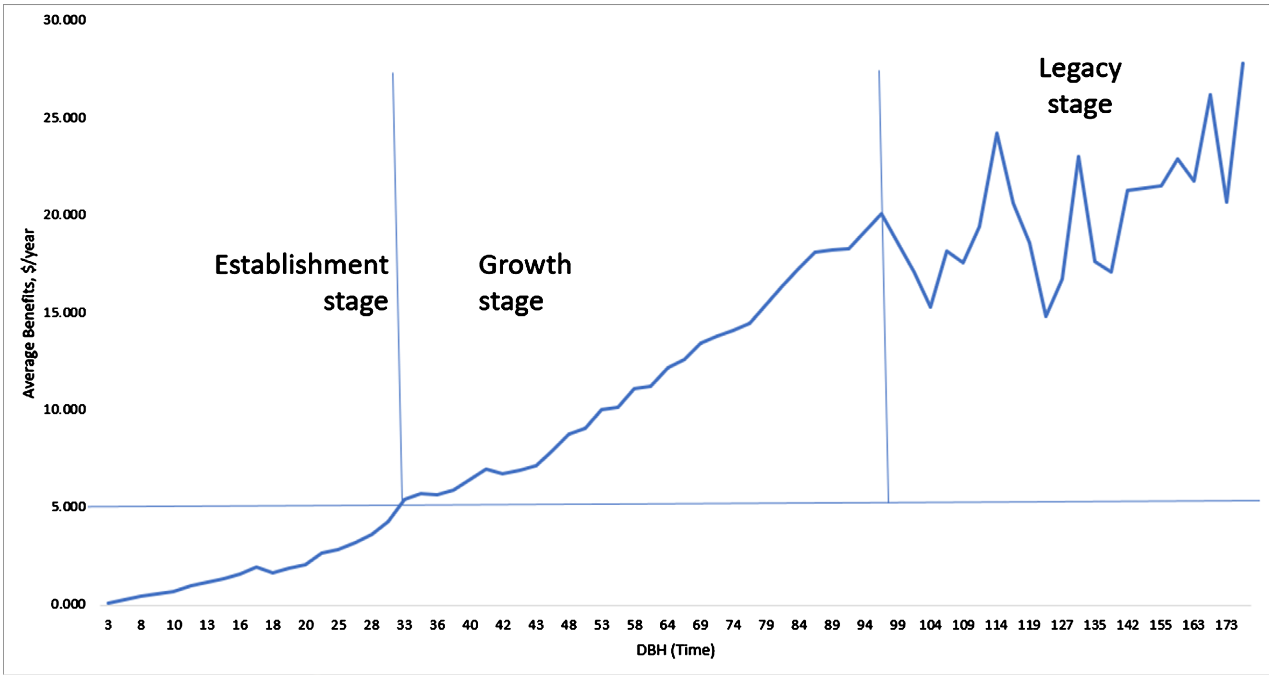

Figure 2. Temporal distribution of average annual benefits ($/year) and the three growth stages (establishment, growth, legacy) in the Clemson urban forest.

curve was broadly segmented into establishment, growth, and legacy stages. The establishment stage, trees with a below-average supply rate (<$4.80/year), was the first stage that typically involved younger trees with a smaller diameter size than the other two stages. With average benefits between $4.80/year to $20.00/year, the growth stage was characterized by tree sizes between establishment and older trees. With average benefits over $20.00/year, the legacy stage included older trees that were more productive and functional than the other two stages. The average benefit rates were \$1.52/year, \$10.03/year, and \$18.67/year for trees in establishment, growth, and legacy stages, respectively (Table 3).

The evidence of outlier observations in the establishment and growth stages indicates higher productivity of a few trees within the groups (Figure 3). It shows that some species outperform others even if they belong to the same group. The legacy stage trees had wider variability in observations than the other two stages, as indicated by longer whiskers for the first and fourth quartile observations.

Table 3. Tree growth stages, frequency, and mean benefit rates for the pollution removal, carbon sequestration, run-off reduction, and structural value in the Clemson urban forest.

Stand growth stages	% of N	% of total benefits	Mean (\$/tree)			
			Pollution	Carbon	Run-off	Structural
Establishment	65	20	0.16	0.98	0.38	548.03
Growth	31	64	1.57	4.77	3.68	4285.21
Legacy	4	16	4.12	4.88	9.66	14,668.26
F-Statistics			5674.46	3637.54	5671.08	11,348.90
P-value			<0.0001	<0.0001	<0.0001	<0.0001

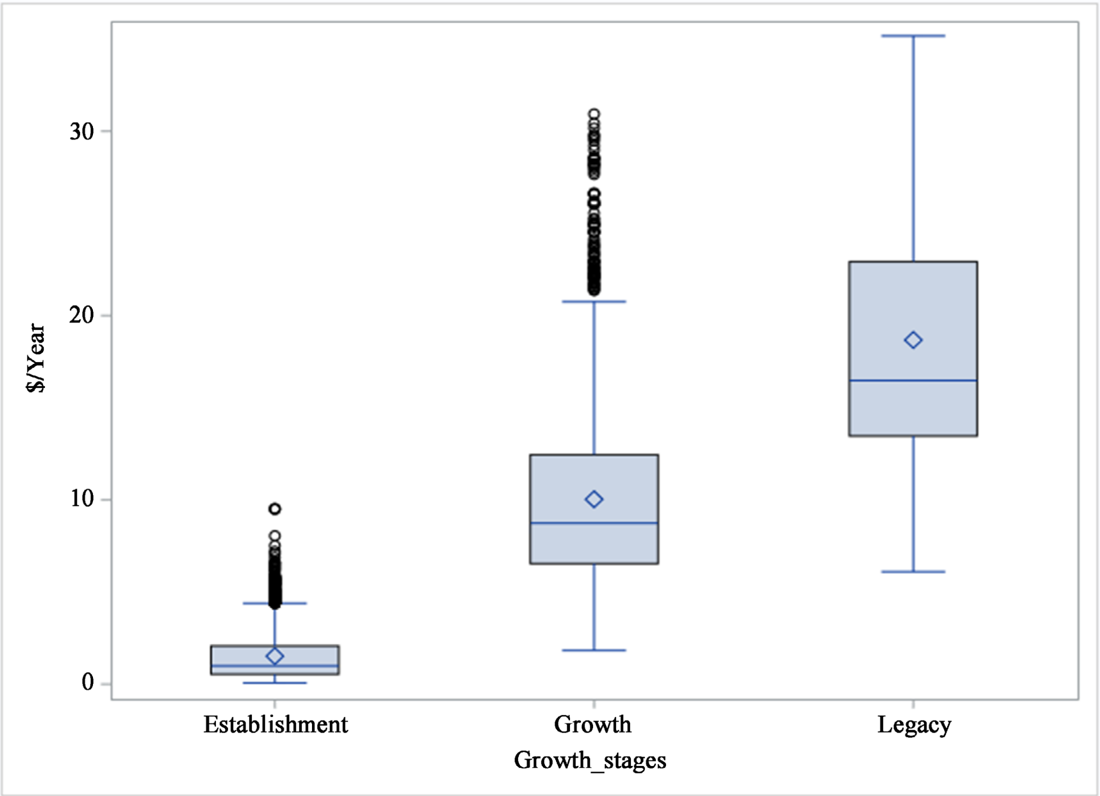

Figure 3. Box plot of total ecosystem benefits among the three growth stages (establishment, growth, and legacy stages) in the Clemson urban forest. Three growth stages (establishment, growth, legacy) were statistically significant in terms of the total ecosystem benefits (F value 6408.90, df 2, P < 0.0001).

Interestingly, there were no outliers in the legacy stage means that maximum observations were within the upper limit. In the box plot, the mean values were higher than the median for all the three stages, indicating that their distributions were positively skewed, i.e., most values were clustered toward the left tail while the right tail was longer.

4. Discussion

This study examined the major factors urban managers will need to consider before harvesting established trees or selecting a new species for plantation. The analysis shows that urban greening needs more than the "*right tree in the right place*" approach in tree planting and management decisions. The results of this study would provide a useful insight to urban forest managers for sustainable urban planning.

Results suggest that all species are not equal in providing ecosystem benefits, so urban centers could be planned to maintain a target ecosystem benefits supply efficiency with a holistic approach to tree species selection and management. A ranking of tree species based on total ecosystem benefits, considering all three benefits CO_2, air quality, and stormwater, Willow oak (*Q. phellos*), Water oak (*Q. nigra*), and River birch (*R. niga*) were preferable tree species in the study area. Similarly, Fox et al. (2020) found Water oak, Willow oak, and Pin oak (Q. palustris) as the top three species in terms of aboveground and belowground carbon storage on the main campus of the University of Georgia. On the other hand, conifer species (Pinus spp) were found to be the top urban-adopted and most efficient tree species for $PM_{2.5}$ removal (Yang et al., 2015). Moreover, Blood et al. (2016)'s study of urban tree species diversity in the southern U.S. found Red maple (*A. rubrum*) and Common crape myrtle (*L. indica*) as the most commonly available species in both private and public properties, akin to species abundances in our study area. Factors such as tree survival, growing space requirement, and plantation cost have been attributed as major factors in species selection decisions (Hauer & Peterson, 2016). Increasing urbanization trends and demand for open spaces in population centers suggest increased emphasis on the neighborhood's supply and demand for particular ecosystem benefits. Including site ecological factors, tree species selection should consider a socio-economic analysis of preferred ecosystem benefits and a suitability analysis of the desired species for planning more functional urban forests. Urban forest managers will need to implement strategic forestry planning practices while making species selection to meet future demand and supply of ecosystem service types in rapidly expanding neighborhoods.

Higher species diversity may not mean an optimal supply of desired ecosystem services. The supply of ecosystem benefits increased with the increase in species richness until the cumulative curve peaked. Likewise, the average benefits curve had a negative trend as not all trees supplied equal services with the increase in the species richness. Species diversity might be serving more cultural, aesthetic, and resiliency functions than the type of ecosystem benefits considered in this study. Earlier studies also highlighted that governing species diversity would need analysis of ecological suitability and environmental benefits (Morgenroth et al., 2016; Ross et al., 2020).

In contrast, monoculture might yield greater ecosystem benefits, but it might rank lower in terms of other values such as aesthetics and resiliency toward invasive pests. In agreement with Hulvey et al. (2013), our results suggest that tree diversity in terms of species, size, and composition could be more helpful in increasing resiliency and ecosystem functions than just the total number of species. A strong correlation ($\rho \geq 0.69$) of parameters, tree diameter, leaf area, height, and crown height with ecosystem benefits indicates that these structural parameters could be useful tools along with species diversity for sustainable and functional urban forest planning.

Temporal trends in ecosystem benefits supply should be an essential factor to consider in urban forest planning, especially before tree removal decisions. Based on the average ecosystem values against time, trees in the study area had three major phases, early, growth, and legacy, for supplying average annual benefits ($/year). These results are different from Vogt et al. (2015)'s study with four hypothetical stages, immature, semi-mature, mature, and senescent, for individual trees with no benefits (zero dollars) at the senescent stage. As long as trees have a live crown, they continue to deliver pollution removal and run-off interception benefits higher than the younger plantations, so the zero benefit rate seems to be an extreme assumption. It seems logical to maintain a good proportion of growth and legacy stage trees for an increased supply of benefits, even if it might increase maintenance costs. In well-managed urban forests, older trees that could become a liability often get removed early for public safety reasons, even if older trees continue to provide more benefits than immature trees. However, trees will increment into higher growth stages after some time, so urban forest managers need to balance their tree removal rates with the growth rate of the existing trees and identify needs to introduce new plantings.

Urban forest managers need to balance competing needs of extra space for older trees and the other development needs. Temporal dynamics of ecosystem supply indicated that legacy trees, in general, provided additional benefits than establishment and growth stage trees. But, several other factors, such as liability issues, tree care needs and costs, and development pressure, could be affecting the frequency of trees in each stage (Dwyer et al., 1992; Vogt et al., 2015; Khanal et al., 2017). It might be a general trend among expanding urban centers to have more establishment stage trees than the other two stages, even if it might be preferable to have more legacy trees from an ecosystem benefits perspective (Pataki et al., 2021). Our study showed a 65% - 31% - 4% frequency distribution among the establishment, growth, and legacy trees supplying ecosystem benefits worth $31,000/year, with the average rate varying between $1.52/tree to $18.67/tree depending on their growth stage. It provides strong empirical evidence that maintaining balanced size composition is very important to supply optimal ecosystem services and sustain them with the forest growth dynamics over time. However, keeping more older trees in an expanding urban environment is easier said than done as it creates several maintenance costs and security issues for urban managers to consider. Hilbert et al. (2019) found that municipalities with legacy (heritage) tree protection ordinances had higher canopy cover rates than urban centers without such provisions. This behavior explains the reluctance of homeowners to incur extra tree care costs for the older (legacy) trees unless required by the law.

Nevertheless, it puts urban forest managers in a delicate balancing position to meet the increasing demand for ecosystem benefits, pollution reduction, runoff removal, health, and social services, while giving equal importance to the ecological needs of those trees. Once those legacy or growth stage trees get removed, there will be a time gap until those establishment stage trees grow to a similar size and compensate for the deficiency in the ecosystem benefits supply. Therefore, a comprehensive and long-term planning approach could only ensure a sustainable and functioning urban forest that would meet increasing demands for ecosystem benefits. It suggests that sustainable urban forestry requires foresight and advance planning, more than just planting of new tree species in unused spaces.

5. Conclusion

Forest stand dynamics is an important concept in classical forestry that often gets little attention in the urban forestry literature. A sustainable supply of ecosystem benefits would need a balance of forest structure in terms of major structural parameters such as total height, DBH, leaf area, and crown height. As the forest structure undergoes changes over time, so does the type and amount of ecosystem services supplied. It would be logical for urban forest managers to identify forest management goals and preferred ecosystem benefits among the urban communities to guide the required forest structure and dynamics needed to sustain the supply of benefits in the long run. A strong human dimension component makes urban forest management a unique practice resulting in multiple socio-economic and environmental implications for the urban communities. Future studies could focus on cost items associated with the stand dynamics for economic and ecological efficiency in managing urban forests.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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