UTM UNIVERSITI TEKNOLOGI MALAYSIA

MINISTRY OF HIGHER EDUCATION

Institute of Landscape Architects Malaysia (ILAM) MALAYSIA

MAJLIS BANDARAYA JOHOR BAHRU

Estimating Carbon Sequestration and Storage by an Urban Forest in Malaysia:

A case study of *Hutan Bandar* MBJB, Johor Bahru

Prepared by: Siti Nur Hannah Ismail

Faculty of Built Environment and Surveying

Universiti Teknologi Malaysia

ACKNOWLEDGEMENT

We gratefully acknowledge the generous funding provided by the Ministry of Higher Education (MoHE) through grant number FRGS/1/2021/WAB02/UTM/02/5 and the Institute of Landscape Architects Malaysia (ILAM) for their financial support under ILAMGRANT-2022-02. Our heartfelt thanks also go to our co-researchers, collaborators, and graduate research assistants for their invaluable assistance and contributions throughout the research process. Their dedication and support were instrumental in the successful completion of this research.

TABLE OF CONTENT

1

INTRODUCTION

1.1 Introduction

Climate change impacts the world and the environment in various ways including rising of temperatures, which contributes to rising sea levels and threatens many living organisms and communities. Extreme weather events such as rainfall, droughts and wildfires become more frequent and severe, disrupting ecosystems, and endangering both wildlife and human populations, aggravating health risks. These changes in precipitation patterns affect agriculture, water resources, and biodiversity, leading to food insecurity and habitat loss, especially in urbanized areas. Urban areas are particularly affected by global warming due to the urban heat island effects, where natural surfaces are replaced with hard impermeable surfaces (i.e., roads, parking lots, plazas, and buildings) (Ismail, 2020). This exacerbates heat transfers from hard surfaces, which increases urban air temperatures and negatively affects the quality of life in urban areas. Anthropogenic activities such as pollution from transports and high energy consumption in operating buildings and factories excessively contribute to the increased CO_2 emissions in urban areas, exacerbating subsequent effects of global warming and climate change. Many cities around the world are striving to mitigate such impacts by emphasizing the achievement towards future low to net-zero carbon cities (Seto et al., 2021), Malaysia included.

1.2 Problem Statement

The effects of climate change and global warming is primarily caused by high rates of carbon emissions in the atmosphere. High concentrations of CO_2 is largely associated with burning of fossil fuels is one of the largest components of the greenhouse gases (GHG) (United Nations, n.d.b). According to the United Nations (n.d.b), global temperature has risen by an average of 0.85°C between 1880 and 2012. To address this, parties to the UNFCCC have agreed to reduce emissions of CO_2 by about 45%t by 2030, to limit the rise of global temperature to 1.5 degrees Celsius.

The urban areas or cities are particularly affected by global warming due to the urban heat island effects, where natural land covers such as grass, soils and green spaces are replaced with pavements and buildings, and other surfaces that absorb and retain heat (Ismail, 2020). Similarly, most carbon emissions in Malaysia occurs in urban areas, where the energy sectors are responsible for almost 80% of total carbon emissions. As an effort to reduce CO_2 emissions, Malaysia has developed a Low-Carbon Cities Framework and Green Technology Master Plan as part of the national decarbonization strategies. According to Kanniah et al., (2014), the importance of green spaces in urban areas and how trees can help with delivering urban ecosystem services have gained more attention in Malaysia recently, and research covering these topics have increasingly emerged. However, studies on the importance of urban forests and its morphological aspects that influences carbon sequestration and storage is still less well researched, and their significance in helping to reduce atmospheric CO_2 is often overlooked in urban planning processes of cities in Malaysia (Kanniah et al., 2014). Thus, in line with the government's policies and strategies as well as global aspirations, this research aimed to determine the potential of urban forests as carbon stock agents to help reduce CO_2 concentrations in urban areas, particularly in Malaysian cities.

1.3 Research Aim and Objectives

This research aims to investigate the current functions and capacities of urban forests in Johor Bahru to help reduce atmospheric CO_2 levels by examining various factors that influence carbon sequestration and storage. Two objectives have been formulated to facilitate the accomplishment of this aim:

1. To determine factors affecting carbon sequestration and carbon stocks by *Majlis Bandaraya* Johor Bahru (MBJB) urban forest.
2. To critically assess actual and potential roles of urban forests in reducing atmospheric CO_2 in Malaysian cities, specifically Johor Bahru.

1.4 Significance of research

This research will be beneficial to professionals in the built environment, especially landscape architects and planners in providing recommendations and guidelines for planning processes of urban forests in relation to carbon storage potentials. The aim to achieve low-carbon cities act as one of the climate change adaptation strategies, while ensuring and enhancing the quality of lives of urban residents – is in line towards achieving the UN Sustainable Development Goals.

1.4.1 Relevance to Government Policy

1. United Nations Framework Convention on Climate Change (UNFCCC):
    - Sustainable Development Goals - Framework
    - Paris Agreement (Ratified 16 November 2016)
    - Kyoto Protocol (Ratified 04 September 2002)
2. National Green Technology Masterplan (2017)
3. Malaysia Low Carbon Cities Framework (LCCF) (2011) / Low Carbon Cities Challenge 2030

2

LITERATURE REVIEW

2.1 Introduction

Urban forests play a pivotal role in mitigating the impacts of climate change by serving as vital carbon sinks through storage and sequestration mechanisms. As rapid urbanization continues to encroach upon natural landscapes, preserving and expanding urban forests becomes a crucial component of green infrastructure and urban development strategies. These forests not only enhance the aesthetic appeal of cities and offer green spaces for social recreation, but also contribute significantly to CO_2 removal from the atmosphere, helping to offset the emissions generated by urban activities. The multifaceted benefits of urban forests as integral elements of sustainable urban development are discussed, focusing particularly on their capacity to store and sequester carbon and fostering resilient and low carbon cities and communities.

2.2 Carbon Emissions Contributing to Global Warming

The concerning rise in carbon emissions continues to be a primary cause of global warming, posing profound challenges to ecosystems, economies, and human well-being. According to recent reports from the Intergovernmental Panel on Climate Change (IPCC) (2021), CO_2 levels in the atmosphere have reached unprecedented levels due to human activities such as the burning of fossil fuels for energy production, transportation, and industrial processes. This influx of carbon dioxide, along with other greenhouse gases amplifies the greenhouse effect, trapping more heat within the Earth's atmosphere. Consequently, this leads to temperature and sea level rise, and causes unpredictable and extreme weather patterns. This affects human and wildlife populations (biodiversity loss), causes food and water insecurity and as well as impacting human health and wellbeing.

Recent research trends focus on addressing carbon emissions to mitigate the impacts of global warming. Advancements in climate modeling techniques have enabled researchers to project the future trajectory of global temperatures and associated impacts under different emission scenarios (Rogelj et al. 2011; Pielke Jr et al., 2022). The Paris Agreement, a landmark international accord aimed at limiting global warming to well below 2 °C above pre-industrial levels, underscores the global consensus on the imperative of reducing carbon emissions (United Nations (n.d.c). To achieve this, implementation of comprehensive mitigation strategies, combined with investments in renewable energy infrastructure, reforestation efforts, and sustainable land use practices, is essential to mitigate the escalating risks posed by carbon emissions and safeguard the health and prosperity of current and future generations.

2.3 Carbon Emissions in Malaysia

Malaysia is listed as one of the countries in East Asia with high carbon emission, among China, Japan, Hong Kong, and a few others (Anwar et al., 2020). Most carbon emissions (up to 80%) in Malaysia occurs within the urban setting, and mainly related to the energy sector (Ministry of Natural Resources and Environment, 2015). Therefore, the urgency for the energy industries to reduce emission is of higher priority. Malaysia have been focusing on reducing dependency on petroleum products and considering impacts towards the environment through promotion of renewable energy as its main priority (Ministry of Natural Resources and Environment Malaysia, 2015). However, being a country that is rapidly developing, this may impose some challenges. According to the Ministry of Energy, Green Technology and Water (KeTTHA) (2017), Malaysia's urban population stands significantly at 76.61% (in 2019) of the total population with a fast-growing rate of 2.5% per year. Thus, as the country's population increases and the need to grow GDPs to alleviate substantial levels of poverty, this is affecting the key driver of Malaysia's economy; fossil fuel, which is evidently a primary contributor emission in Malaysia (Susskind et al., 2020).

Nonetheless, beyond efforts to reduce CO_2 emission by cutting down on energy sector, there are also other opportunities and strategies for other sectors to achieve these reductions. One of the paths in which the country can establish low-carbon cities is by promoting 'green cities' concept. This can be implemented by increasing areas of and preserving greeneries in urban areas. In relevance, Susskind et al., (2020) highlighted that Malaysia's intensity of carbon emissions were reduced when calculation included land use and forestry sector emissions. It was reported that emissions were reduced to almost 75% by forest gazetting (Ministry of Natural Resources and Environment, 2015). Designating green spaces and forests in urban areas can significantly reduce carbon emissions by enhancing the natural absorption of carbon dioxide (CO2). Trees and plants in these green spaces act as carbon sinks, absorbing CO2 from the atmosphere during photosynthesis and storing it in their biomass. Additionally, green spaces encourage walking and cycling by providing pleasant environments, which can reduce reliance on vehicles and further cut emissions. By incorporating more green areas, cities can improve air quality, promote biodiversity, and create healthier, more sustainable urban environments. Therefore, strategic urban planning needs to be considered sooner than later to achieve a more inclusive and sustainable urbanization in the near future. As a driving force to the development of green cities, KeTTHA and the Malaysian Green Technology Corporation have launched the Low Carbon Cities Framework (LCCF); a national framework to assist local municipalities and developers to achieve low-carbon cities by 2030 (KeTTHA, 2017). By adopting these green practices, not only the country will be able to mitigate global warming effects, but also protecting and providing for the urban ecosystems as well as enhancing environmental, health and social benefits while improving the quality of urban lives; thus, complying with the United Nation’s Sustainable Development Goals.

2.4 Roles of Urban forests and Trees in Carbon sequestration and Storage

Ecosystems such as forests, peatlands, wetlands, and the ocean play a crucial role in removing carbon from the atmosphere, thereby helping to reduce the intensity of global warming. Due to the growing rate of urban population, urban forests, or urban greeneries in general are becoming increasingly important to urban ecosystem resilience (Amoatey and Sulaiman, 2020). Urban forests are essentially defined as a collection of trees that are planted in an urban setting. These include trees in parks, street trees, wetlands and/or other natural areas (Kanniah and Siong, 2018). Urban forests are known as, and often promoted as nature-based solution for mitigating climate change in cities (Kanniah and Siong, 2018).

Fig. 1. Urban forests play a crucial role in counteracting atmospheric CO2 resulting from human activities in urban areas (Image source: Charles, 2016).

Trees and forests represent one of the most effective natural systems for capturing carbon within our environment through a process called carbon sequestration. In this process, trees extract (sequester) carbon from the atmosphere through photosynthesis and consumes it as food (Fares et al., 2017). Carbon atoms are then separated from the oxygen atoms, subsequently releasing oxygen to the atmosphere though respiration (Prabha et al., 2013). As a result, carbon is stored within tree structures such as leaves, bark, and trunk (above-ground biomass) and in the soil (below-ground biomass), creating a pool of carbon in the forests (Prabha et al., 2013), called the carbon stock. The wooden structure of a tree lasts for years as a standing tree, and hardwood species may take up to 70 years to break down after it dies, in which carbon will be released back into the air during the decomposition process. The rate at which carbon sequestrations (and storage) take place differs among forests/trees and is influenced by many factors. These include local temperature, rainfall, topography, and soil characteristics (Pragasan, 2020). Tree characteristics such as species richness, structure (height and diameter), leaf characteristics, density of woods and tree stage (and size) all affects the rate in which carbon is sequestered and stored (Misni et al., 2015; Amoatey and

Sulaiman, 2020; Lahoti et al., 2020). For example, trees possessing broad leaves may be advantageous in that it can absorb more carbon content due to larger leaf surface area, however, other aspects of the tree such as leaf texture, canopy structure and bark/trunk layers may also affect the sequestration process.

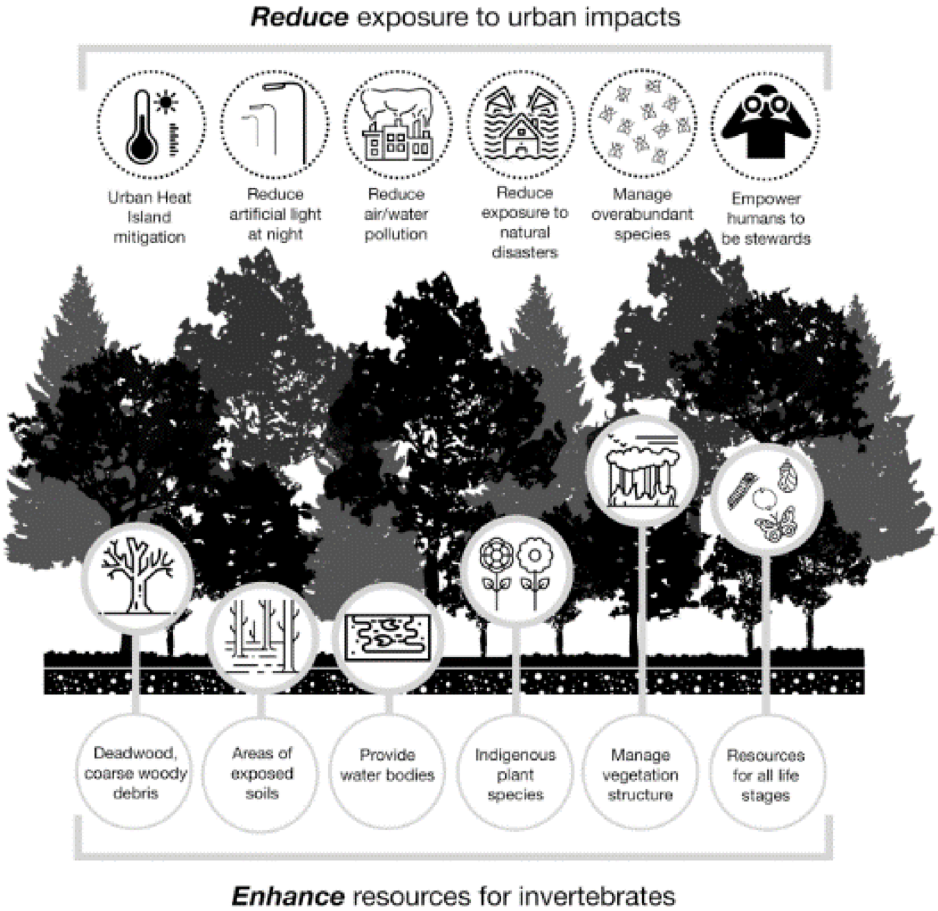

Fig. 2. Some ecosystem services offered by urban forests emphasizing on reducing exposure to urban impacts and enhancing biodiversity offered by urban forests (Kotze et al., 2022).

Forests accounts for 70–90% of terrestrial aboveground and belowground and aboveground biomass in particular holds approximately between 70% and 90% of total forest biomass (Houghton et al., 2009), particularly tropical forests, which are found to be able to sequester 0.5 gigatonnes of carbon globally each year (Kachur, 2017). Pine, spruce, larch, beech, alder, oak, and birch forests are among the species which capture large amounts of carbon, though this considers carbon content in the forest soil ecosystem (e.g. 84 Mg ha-1 by pine forest and 409 Mg ha-1by alder forest) (Nowalska et al 2020). However, as urbanization replaces natural land surfaces including forests, urban areas risk losing a large portion of carbon sinks, which aggravates carbon accumulation in urban atmosphere. Thus, optimizing the preservation of forests during a city expansion needs to be prioritized as urban forests not only act as healing sanctuaries in cities but also serve multiple urban ecosystem services and minimize any of urban environmental risks associated to greenhouse gases and atmospheric CO_2It is also worth noting that greeneries located within an urban setting may significantly affect local CO_2 concentrations compared to rural areas, where lower CO_2 concentration is associated with more presence of vegetation and natural areas (Fares et al., 2017; Lahoti et al., 2020). According to Fares et al., (2017), while higher concentration of CO_2 may promote more efficient photosynthesis by urban trees, thus sequester more carbon, trees planted in an urban environment may also experience environmental stresses that can compromise their photosynthetic abilities. Nonetheless, with the severity of global warming and rapid rate of urban developments, the presence of forests within an urban area are of great importance and are in greater need now more than ever. Therefore, to optimize carbon removal from the urban atmosphere, the implementation of urban forests needs to be carefully considered with strategic planning development based on knowledge on planting schemes and indicators that this research aims to achieve as one of its objectives.

3

RESEARCH METHODOLOGY

1.1 Study site

The study area encompasses the *Majlis Bandaraya* Johor Bahru (MBJB) urban forest, situated in Johor Bahru, Johor, the southernmost state of Peninsular Malaysia (Fig. 3). On average, Johor experiences tropical climate, characterized by an average annual temperature of 26.3°C and significant rainfall, averaging 2662 mm annually (Climate-Data.org, n.d.). The MBJB urban forest, located approximately 1.5 km from Johor Bahru's city center, covers an area of 56.52 acres. This site was selected for its strategic location within the urbanized city center, surrounded by government offices, educational institutions, and residential areas. The urban forest boasts a dense vegetation cover, accounting for 59.93% of the area, with stands aging up to 31 years since its establishment in 1993 (Fauzi and Ghafar, 2020).

Fig. 3. Location plan (top right) and aerial image of the MBJB urban forest, Johor, Malaysia.

1.2 Data collection

This study employs field data to estimate Above-ground Biomass (AGB) and carbon stock values, using a regression allometric equation developed by Chave et al. (2005) (Eq. 1). Carbon storage by each tree species were estimated using Chave's equation because Chave's equation is recommended for estimating biomass in tropical forests and is widely utilized. In cases where no specific allometric equation was available for individual species, the average results from equations of the same genus were used. This approach ensures a comprehensive estimation of AGB across diverse tree species. Chave's equation incorporates data on DBH in centimeters, Height (H) in meters, and wood density (ρ) in grams per cubic centimeter. Wood density values (ρ) for various tree species were sourced from the global wood density database (Zanne et al., 2009). To calculate the carbon stock of each tree within the sampling plots, a conversion factor of carbon was applied, with a value of 0.47, as recommended by the Intergovernmental Panel on Climate Change (IPCC, 2006).

$$AGB = 0.0673 \times (\rho \times DBH^2 \times H) \qquad \text{(Eq. 1)}$$

Where:

ρ = Wood density for each species (in g cm^{-3})
DBH = Diameter at breast height (in cm)
H = Tree height (in m)

Field data were used to determine the urban forest structure (i.e., tree species composition, species diversity, distribution, and number of trees) as well as to estimate the AGB using tree biometric data, which consist of diameter at breast height (DBH) and tree heights (Fig. 4). The data collection was based on random sampling of ten plots within the MBJB urban forest area. Each plot was established in a rectangular size of 15 meters by 10 meters (Fig. 5) and the plots featured a diverse array of vegetation species, types, and sizes. The sampling plots were strategically positioned near existing walking trails to facilitate accessibility. Tree height measurements were conducted using the single pole method, for measuring the height of vertical trees. Diameter at Breast Height measurements were taken at 1.3 meters above ground level. Upon completion of plot setup, tree species identification was carried out by a botanist expert from Universiti Kebangsaan Malaysia (UKM).

Fig. 4. Example of tree tagging at the MBJB urban forest site.

Fig. 5. Example of plot sample on the MBJB urban forest site.

4

FINDINGS AND DISCUSSION

4.1 Introduction

The findings in this study are discussed within several sub-topics, namely tree size distribution and categorization, tree species diversity, carbon storage performance by the observed tree species as well as the influencing factors affecting carbon storage by different trees species. This exploration is crucial because carbon sequestration rates and storage capacities vary among species, with factors influencing these differences differing among species as well. Therefore, it is imperative to identify the traits, advantages, tolerances, and disadvantages of different species to propose suitable planting schemes for urban forests and incorporate these recommendations into urban planning strategies.

4.2 Tree Size Categorization and Species Diversity

Based on tree inventory that were conducted within the sample plots, trees were categorized into four different categories: small trees (<7.62 m), medium trees (7.62 m - 12.20 m), large or mature trees (12.2 m- 30.2 m) and trees with extreme height (>30.2 m). Based on these categories of tree size, there were 5 small trees, 8 medium trees, 59 large trees and 18 trees with extreme height (Fig. 6). The DBH of 90 trees recorded on site ranged between 3 cm and 86 cm, while tree height ranged between 2 m and 45 m. The tallest species recorded were by *K. senegalensis* and *V. pubescens* at 45 m.

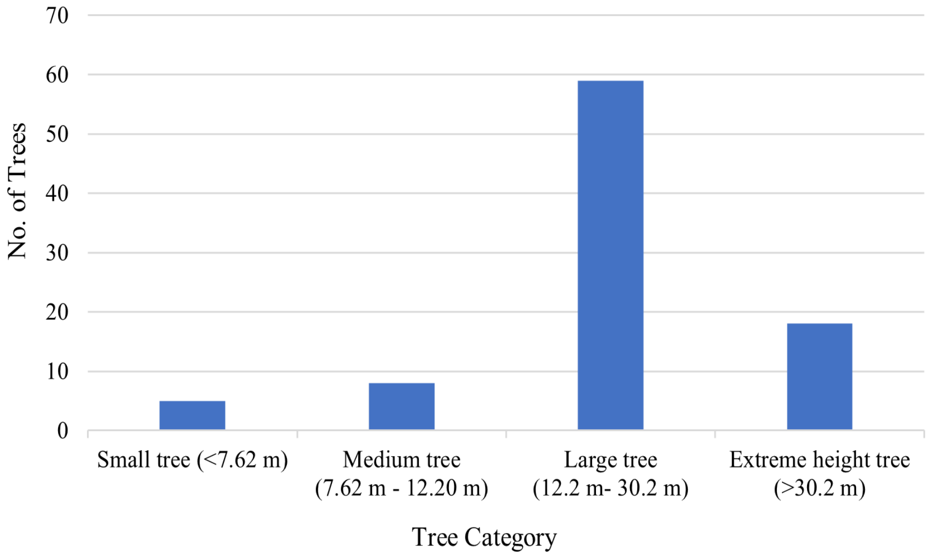

Fig. 6. Tree size distribution chart of the observed trees in MBJB urban forest, Johor Malaysia.

A total of 90 trees that were investigated on site represented a diverse array of flora, comprising 22 species from 14 different families (refer to Table 1). Notably, most of these species are recognized as native to the region, indicative of the site's natural forest composition. Five species—namely *A. mangium, A. excelsa, H. brasiliensis*, *K. senegalensis*, and *S. malaccense*—were identified as non-native to Malaysia. However, despite their non-indigenous status, these species originate from tropical and subtropical climates, suggesting their potential adaptability to the local environment.

Based on the field survey, 22 species within the 10 sampling plots were identified covering an area of 1500 m^2. This showed a relatively rich diversity of tree species and provides a robust quantitative descriptor of the urban forest structure. Such diversity is crucial because it contributes to a complex forest structure, encompassing a varied mix of species richness and leaf characteristics (Lahoti et al., 2020). It is often recognized that high tree species richness (diversity), structure and composition is correlated with increased carbon sequestration and storage capabilities within ecosystems. Therefore, the presence of diverse species within the MBJB urban forest indicates a promising potential for effective carbon sequestration and storage, contributing positively to mitigating climate change impacts.

Table 1. List of tree species observed at the MBJB urban forest site, Johor Bahru.

No	Family	Tree species
1	Fabaceae	*Acacia mangium*
2	Pentaphylacaceae	*Adinandra dumosa*
3	Apocynaceae	*Alstonia angustiloba*
4	Meliaceae	*Azadirachta excelsa*
5	Centroplacaceae	*Bhesa paniculata*
6	Hypericaceae	*Cratoxylum cochinchinense*
7	Hypericaceae	*Cratoxylum formosum*
8	Gentianaceae	*Cyrtophyllum fragrans*
9	Pentaphylacaceae	*Eurya acuminata*
10	Gnetaceae	*Gnetum gnemon*
11	Euphorbiaceae	*Hevea brasiliensis*
12	Dipterocarpaceae	*Hopea odorata*
13	Meliaeae	*Khaya senegalensis*
14	Fabaceae	*Koompasia excelsa*
15	Lauraceae	*Litsea elliptica*
16	Malvaceae	*Sterculia parviflora*
17	Myrtaceae	*Syzygium grande*
18	Myrtaceae	*Syzygium malaccense*
19	Myrtaceae	*Syzygium myrtifolium*
20	Myrtaceae	*Syzygium polyanthum*
21	Lamiaceae	*Vitex pinnata*
22	Lamiaceae	*Vitex pubescens*

Forest structure and composition are important indicators influencing forest carbon storage (Wei et al., 2024). This research reported that most trees are within the large tree categories (Fig. 6), with DBH and height ranging from 11.5 cm to 56 cm for DBH, and from 12.2 m to 30.2 m for height respectively. This indicates that most of these trees were planted between 10 to 30 years ago, therefore the MBJB urban forest can be categorized as a relatively 'young' forest (Simkin et al., 2020 classified middle-aged forests to be between the age 40 and 80 years, while more 'older' or mature forests tends to be of 81–120 years of age). Mature trees (> 45 years old) are frequently reported to able to store more carbon due to larger DBH and presumably taller heights thus having more upper crown canopy. However, younger forests may also tend to sequester carbon at a faster rate due to higher photosynthesis rate (growing rate) and because more trees can be arranged and crowded together due to its smaller size, which is particularly crucial in limited spaces in urban areas. This could potentially address the challenge of limited green space in urban areas while also enhancing the carbon sequestration rates of urban forests. While it is contended that small trees may eventually mature into larger trees and starts competing for light, resources, and growing space, this is not universally true for all trees. Thus, it is crucial to grasp ecological planting principles and carefully choose species mixes and communities that can coexist and flourish together. Moreover, when small trees perish and decompose, they release minimal carbon compared to older, more mature trees (Norman and Kreye, 2023), while the surviving trees continue to grow and sequester more carbon as the forest matures. It is therefore essential to start recognizing that the optimal tree planting strategy that involves a balanced mixture of young and old trees, as well as trees of varying heights and species richness.

4.3 Carbon Storage by Species

Carbon storage for each species was taken as the average based on the number of trees of each respective species. By species, *K. senegalensis* stored the most carbon with 15.34 t/ha, followed by *A. mangium* (14.07 t/ha), while *C. cochinchinense* stored the least (0.03 t/ha) (Fig. 7). Results are taken based on the overall mean of each species.

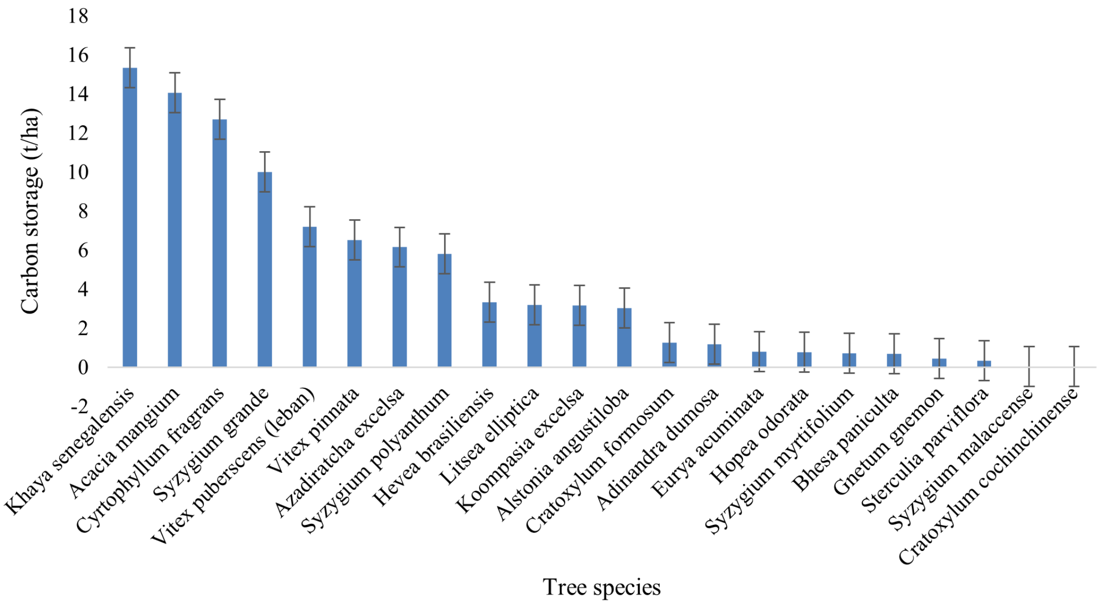

Fig. 7. Carbon Storage by species in MBJB urban forest, Johor, Malaysia.

As carbon storage is highly related with size and health of the trees, the study found a positive correlation between the amount of carbon stored in the tree biomass. As reported above, *K. senegalensis* stored the most carbon with 15.34 tCO_2/ha, closely followed by *A. mangium* (14.07 tCO_2/ha) and *C. fragrans* (12.71 tCO_2/ha). This was found to be highly associated with heights of trees by these species. The tree height range for *K. senegalensis* were 8 m to 45 m, with an average of 29 m in height. Most of *K. senegalensis* trees that were measured on the site falls within the extremely tall tree category (>30.2 m), had amongst the tallest trees that were observed in this study. Similarly, *A. mangium* tree height ranged between 22 m to 33 m, and *C. fragrans* ranged between 19 m to 34 m. Trees with lower height such as *C. cochinchinense, S. malaccense* and *S. parviflora* all generally contributed to low carbon storage (0.03, 0.04 and 0.33 tCO_2/ha). Taller trees generally have more biomass because they have grown for longer periods and have more extensive structures. Biomass is directly related to the amount of carbon stored since a significant portion of a tree's biomass consists of carbon. As trees grow taller, their trunks and branches become larger, increasing the tree's overall volume. This increased volume translates to more space for carbon storage within the tree's tissues.

Similarly, the DBH of the top 3 species that captured and stored the most carbon, *K. senegalensis* were among the largest, ranging from 14 cm to 86 cm, *A. mangium*, from 38.6 to 81 m, and *C. fragrans,* from 15 cm to 63 cm. This is consistent with their carbon storage performance as well as overall tree heights. Interestingly, *A. excelsa* also had relatively large DBH (ranging between 30.5 m to 47 m) and *H. brasiliensis* consistently had medium to large DBH (ranging between 20.3 m to 52 m), but these species performed moderately to low in terms of carbon capture and storage. Both species had tree heights that were categorized between large and extra-large trees, but stored carbon at 6.15 tCO_2/ha (*A. excelsa*) and 3.32 tCO_2/ha (*H. brasiliensis*), which were relatively low. In general, larger DBH may indicate a more mature and robust tree, which usually means it has accumulated more biomass and thus more carbon over time. The relationship between DBH and carbon storage also involves the tree's wood density. Trees with a larger DBH typically have denser wood, which can store more carbon per unit volume compared to trees with smaller DBH.

4.4 Influence of Tree Characteristics on Carbon Sequestration and Storage

Essentially, carbon sequestration and storage by trees are influenced by several factors including tree characteristics and species type, growth rates, age, and size. All these factors influence the rate of carbon uptake and storage capacities as well as he health of a tree impacts its ability to sequester carbon, with healthier trees capturing more carbon dioxide through photosynthesis. Understanding these characteristics helps in managing and planning for urban forests and planting strategies to maximize carbon storage and mitigate climate change. Factors contributing to carbon storage by trees are discussed below.

4.4.1 Tree wood density

The mass of carbon in trees depends on the volume and density of their wood. Trees with higher wood density grow more slowly because the photosynthetic process is slow, making carbon sequestration gradual. However, these trees ultimately store much more carbon than those with lower wood density and faster growth rates. According to Hamdan (2021), species with low wood density also tend to have higher mortality rates and often die young (around 10-20 years), whereas species with high wood density can live much longer, sometimes up to hundreds of years. There is often a trade-off between wood density and growth rate. Fast-growing species typically have lower wood density but can sequester carbon quickly over a shorter period. However, slower-growing species with denser wood store more carbon over their longer lifespans (Shimamoto et al., 2014). Trees with denser wood are generally more resistant to decay and environmental stress, which means the carbon stored in them remains sequestered for longer periods. This long-term sequestration is crucial for mitigating climate change.

A mix of tree species with varying wood densities can also positively impact the ecosystem by enhancing the resilience and biodiversity of forests (Bauhus et al., 2017). Diverse ecosystems are better at adapting to changes and can sequester more carbon overall. Therefore, effective forest management should consider wood density to maximize carbon sequestration. Strategies may include planting a combination of fast-growing species for immediate carbon uptake and slow-growing, dense-wood species for long-term storage. Thus, balancing species with different wood densities and growth rates can optimize carbon sequestration in urban and natural forests, contributing significantly to climate change mitigation efforts.

4.4.2 Growing conditions and growth characteristics

Growth conditions and tree characteristics significantly influence carbon storage in several ways. Optimal growth conditions, such as adequate sunlight, water, and nutrient availability, enhance a tree's growth rate and biomass accumulation, leading to greater carbon sequestration (Arilouma et al., 2021). In terms of climate, warmer temperatures generally increase photosynthesis rates, leading to faster growth and higher carbon sequestration, but extreme heat can stress trees and reduce their growth. Similarly, adequate water availability promotes healthy tree growth, enhancing carbon uptake, while drought conditions, however, can limit growth and reduce carbon sequestration.

Soil quality and climate also play a vital role, with fertile soils and favorable climatic conditions supporting robust tree growth and higher carbon storage. Soils rich in essential nutrients with well-drained, aerated soils support vigorous tree growth, leading to greater biomass accumulation and carbon storage. Tree characteristics, including species, age, and health, further impact carbon storage. While older trees typically store more carbon, healthier trees tend to sequester carbon more efficiently. In dense forests, competition for light can limit the growth of understory trees. Open spaces or managed thinning can enhance light penetration, boosting growth and carbon uptake.

4.4.3 Tree size

The result of this study found positive correlation between taller trees and larger DBH with higher amount of stored carbon in the tree biomass. This result is consistent with several previous research (Bradford et al.,2019; Besar et al., 2020; Noulèkoun et al., 2023), which found that higher carbon storage is associated with larger DBH and taller trees. This is because taller and older trees tend to be denser and thus store carbon more proportionately compared to smaller trees. Larger and taller trees not only have consistent access to the sun (taller canopy reaching the top) to use solar energy for photosynthesis, but large trees also tend to have a greater number of leaves to absorb CO_2. Therefore, preserving an old or mature urban forest must be prioritized because the more mature trees that are felled, higher amounts of carbon will be released.

Khaya senegalensis's high carbon storage may be also attributed to the moisture rich growing conditions of tropical climate in Malaysia compared to its dry African origin. This species is known to have a high growth performance and biomass accumulation (Warnasooriya & Sivananthawerl, 2016), which compensates for higher photosynthesis rate and carbon sequestration rate. Due to this species being mostly within the category of larger to extreme large tree size, this may also mean that the trunk has higher density value, which was also observed by El Kateb et al, (2022).

4.4.4 Canopy structure

Canopy structure significantly influences carbon sequestration and storage by affecting the amount of sunlight that penetrates through to lower leaves and the forest floor. This in turn impacts photosynthesis and overall biomass production. A dense, well-developed canopy with multiple layers can enhance light capture and increase photosynthetic activity, leading to higher carbon uptake, which was observed with *K. senegalensis*, *A. mangium* and *C. fragrans*. these species having dense and expanding canopy with many woody branches, therefore likely a larger above-ground biomass. Additionally, a complex canopy structure supports greater biodiversity, which can improve ecosystem stability and resilience, further aiding carbon storage. Canopy gaps and variations in canopy height can also promote growth in understory vegetation, contributing to additional carbon sequestration. Therefore, the structure of the canopy is a key factor in determining a forest's capacity to sequester and store carbon.

4.5 Recommendations for Increasing Carbon Storage by Urban Forests

The study suggests that there is significant potential to increase carbon storage within the MBJB urban forest by enhancing its structural diversity. Key recommendations for achieving this are discussed below:

i. Diversify species

Planting a diverse mixture of tree species, including the recommended *K. senegalensis*, *A. mangium*, and *C. fragrans*, can improve the resilience and carbon sequestration capabilities of the urban forest. Diverse species can occupy different ecological niches and contribute to a more stable and productive ecosystem.

ii. Structural Complexity

Increasing the vertical and horizontal complexity of the forest can enhance its carbon sequestration potential. Vertical complexity involves having multiple layers of vegetation (ground cover, shrubs, understory trees, and canopy trees), while horizontal complexity refers to a varied spatial arrangement of trees and plants across the forest.

iii. Dense Planting in Appropriate Areas

While pathways and open spaces are necessary for recreation, areas not designated for such uses could be planted more densely. This approach would involve carefully planning the distribution of trees and vegetation to balance recreational use with ecological function.

iv. Management and Maintenance

Ongoing management practices such as regular monitoring, pruning, and replacement of trees can ensure the forest remains healthy and continues to grow optimally. Healthy, growing trees sequester more carbon than mature trees in a state of decline.

5

CONCLUSION

The research emphasizes the significant role of tree attributes such as species, height, canopy structure, trunk size, and growing conditions in the capacity of trees to sequester and store carbon in their above-ground biomass. Specifically, the study highlights three tree species—*Khaya senegalensis*, *Acacia mangium*, and *Cyrtophyllum fragrans*—as particularly effective for urban forest plantings aimed at enhancing carbon sequestration and storage. These species were found to be useful candidates due to their promising characteristics that favor carbon uptake and storage, making them suitable candidates for urban forestry projects.

Urban forests are seen as a vital tool in the fight against rising atmospheric CO_2 levels. By carefully selecting and planning the planting of diverse tree species and creating multilayered forest structures, urban planners can maximize the carbon sequestration potential of these green spaces. The multiple layers refer to different heights and types of vegetation, from ground cover and understory plants to the upper canopy, which together create a more complex and efficient system for capturing and storing carbon. The MBJB Urban Forest in Johor Bahru serves as a practical case study for this research. Located centrally in the rapidly growing Johor Bahru city center, this urban forest primarily functions as a recreational area. Currently, its forest structure is described as suboptimal, with sparse tree planting to allow for pathways and some areas lacking understory vegetation. This layout, while beneficial for recreational use, limits the forest's capacity to sequester and store carbon efficiently.

Beyond carbon sequestration, a well-planned urban forest offers numerous other ecosystem services that improve the quality of life for urban residents. These include air and water purification, temperature regulation through shading and evapotranspiration, noise reduction, habitat for wildlife, and aesthetic and recreational benefits. A diverse and well-structured urban forest can thus serve as a critical component of urban infrastructure, contributing both to environmental sustainability and human well-being.

In conclusion, while the MBJB Urban Forest currently has a suboptimal structure for maximizing carbon sequestration, there is considerable potential for improvement. By adopting diverse and multilayered planting strategies, enhancing species diversity, and focusing on the structural complexity of the forest, significant gains in carbon storage can be achieved. These improvements not only help mitigate climate change by reducing atmospheric CO_2 but also provide a range of ecosystem services that enhance the quality of life for urban residents.

REFERENCES

Amoatey, P., & Sulaiman, H. (2020). Quantifying carbon storage potential of urban plantations and landscapes in Muscat, Oman. *Environment, Development and Sustainability*, 22(8), 7969-7984.

Bauhus, J., Forrester, D. I., Gardiner, B., Jactel, H., Vallejo, R., & Pretzsch, H. (2017). Ecological Stability of Mixed-Species Forests. In Pretzsch, H., Forrester, D., & Bauhus, J. (Eds.), Mixed-Species Forests (pp. 1-26). Springer, Berlin, Heidelberg. https://doi.org/10.1007/978-3-662-54553-9_7

Besar, N. A., Suardi, H., Phua, M.-H., James, D., Mokhtar, M. B., & Ahmed, M. F. (2020). Carbon Stock and Sequestration Potential of an Agroforestry System in Sabah, Malaysia. *Forests,* 11(2), 210. https://doi.org/10.3390/f11020210

Bradford, M., & Murphy, H. T. (2019). The importance of large-diameter trees in the wet tropical rainforests of Australia. *PLoS One*, 14(5), e0208377. https://doi.org/10.1371/journal.pone.0208377

Charles, (2016, December 12). Urban Forest. *New Straits Times*. Retrieved May 27, 2024, from https://www.nst.com.my/news/2016/12/193513/urban-forest?m=1

Chave, J., Andalo, C., Brown, S., Cairns, M., Chambers, J. C., Eamus, D., Fölster, H., Fromard, F., Higuchi, N., Kira, T., Lescure, J., Nelson, B. W., Ogawa, H., Puig, H., Riéra, B., & Yamakura, T. (2005). Tree allometry and improved estimation of carbon stocks and balance in tropical forests. *Oecologia*, 145(1), 87-99.

Climate-Data.org. (n.d.). Climate Data - Climate information for every country all around the world. Retrieved April 3, 2024, from https://en.climate-data.org/#google_vignette

El Kateb, H., Zhang, H. and Abdallah, Z. (2022) Volume, biomass, carbon sequestration and potential of desert lands' afforestation irrigated by wastewater on examples of three species, Forest Ecology and Management, 504, 119827. Doi: https://doi.org/10.1016/j.foreco.2021.119827

Fares, S., Paoletti, E., Calfapietra, C., Mikkelsen, T. N., Samson, R., & Le Thiec, D. (2017). Carbon Sequestration by Urban Trees. In F. Ferrini, C. Konijnendijk van den Bosch, & A. Fini (Eds.), The Urban Forest (pp. 31-39). Springer, Future City 7.

Fauzi, A. M., & Ghafar, A. A. (2020). Cultural Practices Generated by Structural Biodiversity of Two Urban Forests in Johor Bahru, Malaysia. *International Journal of Built Environment and Sustainability*, 7(2), 15-23.

Hamdan, O. (2021). Wood density variations and carbon sequestration rate of Red List trees. In Proceedings of Regional Webinar on Ex-Situ Conservation and Carbon Sequestration Potential of Red List Tree Species (FRIM Proceedings No. 21). Forest Research Institute Malaysia (FRIM).

Houghton, R. A., Hall, F., & Goetz, S. J. (2009). Importance of biomass in the global carbon cycle. *Journal of Geophysical Research*, 114, G00E03. https://doi.org/10.1029/2009JG000935

IPCC (2006) Good practice guidelines for national greenhouse gas inventories. Switzerland: Intergovernmental Panel on Climate Change

Ismail, S. N. H. (2020). Rainwater retention and evapotranspiration as affected by groundcover plants: The influence of leaf morphology (PhD thesis, University of Sheffield, United Kingdom).

Kachur, T. (2017). As trees age, their climate benefit grows. *CBC News*. Retrieved May 27, 2024, from https://www.cbc.ca/news/canada/how-old-trees-help-climate-1.4252888

Kanniah, K. D., Muhamad, N., & Kang, C. S. (2014). Remote sensing assessment of carbon storage by urban forest. *IOP Conference Series: Earth Environmental Science*, 18, 1-6.

Kanniah, K. D., & Siong, H. C. (2018). Tree Canopy Cover and Its Potential to Reduce CO2 in South of Peninsular Malaysia. *Chemical Engineering Transactions*, 63, 13-18.

Kotze, D. J., Lowe, E. C., & MacIvor, J. S. et al. (2022). Urban forest invertebrates: how they shape and respond to the urban environment. *Urban Ecosystems*, 25, 1589-1609. https://doi.org/10.1007/s11252-022-01240-9

Lahoti, S., Lahoti, A., Joshi, R. K., & Saito, O. (2020). Vegetation structure, species composition, and carbon sink potential of urban green spaces in Nagpur City, India. Land, 9(4), 1-20.

Misni, A., Jamaluddin, S., & Kamaruddin, S. M. (2015). Carbon sequestration through urban green reserve and open space. *Planning Malaysia*, 13, 101-122.

Ministry of Energy, Green Technology and Water. (2017). Green Technology Master Plan Malaysia (pp. 1-196).

Ministry of Natural Resources and Environment. (2015). Malaysia Biennial Update Report To The UNFCCC (pp. 1-174).

Noulèkoun, F., Mensah, S., & Kim, H. et al. (2023). Tree size diversity is the major driver of aboveground carbon storage in dryland agroforestry parklands. Scientific Reports, 13, 22210. https://doi.org/10.1038/s41598-023-49119-9

Norman, J., & Kreye, J. (2023). How forests store carbon. *Penn State Extension*. https://extension.psu.edu/how-forests-store-carbon#:~:text=Young%20trees%20grow%20quickly%20and,carbon%20as%20the%20forest%20matures

Pielke Jr, R., Wigley, T. M. L., Green, C., & Gluckman, J. P. (2022). Plausible 2005–2050 emissions scenarios project between 2 °C and 3 °C of warming by 2100. *Environmental Research Letters*, 17(2), 024027.

Pragasan, L. A. (2019). Tree carbon stock and its relationship to key factors from a tropical hill forest of Tamil Nadu, India. *Geology, Ecology, and Landscapes*, 5(2), 1-8.

Rogelj, J., Hare, W., Lowe, J. et al. (2011). Emission pathways consistent with a 2 °C global temperature limit. *Nature Clim Change*, 1, 413-418. https://doi.org/10.1038/nclimate1258

Seto, K. C., Churkina, G., Hsu, A., Keller, M., Newman, P. W. G., Qin, B., & Ramaswami, A. (2021). From Low- to Net-Zero Carbon Cities: The Next Global Agenda. *Annual Review of Environment and Resources*, 46(1), 377-415.

Shimamoto, C. Y., Botosso, P. C., & Marques, M. C. M. (2014). How much carbon is sequestered during the restoration of tropical forests? Estimates from tree species in the Brazilian

Atlantic forest. *Forest Ecology and Management*, 329, 1-9. https://doi.org/10.1016/j.foreco.2014.06.002

Simkin, J., Ojala, A., Tyrväinen, L. (2020) Restorative effects of mature and young commercial forests, pristine old-growth forest and urban recreation forest - A field experiment, Urban Forestry & Urban Greening, 48, 126567. Doi: 10.1016/j.ufug.2019.126567

Susskind, L., Chun, J., Goldberg, S., Gordon, J. A., Smith, G., & Zaerpoor, Y. (2020). Breaking Out of Carbon Lock-In: Malaysia's Path to Decarbonization. *Frontiers in Built Environment*, 6, 21.

Surya Prabha, A. C., Senthivelu, M., Krishna Kumar, N., & Nagendran, S. (2013). Urban Forests and their Role in Carbon Sequestration: A Review. *International Journal of Forest Research*, 16(1), 23-29.

Torri, L., Ding, H., Di Matteo, G., Leemans, R., & Tan, K. H. (2014). Estimating carbon storage potential in Malayan rainforests and the effects of logging using allometric models. *Environmental Research Letters*, 9, 034018. https://doi.org/10.1088/1748-9326/9/3/034018

United Nations. (n.d.-a). Goal 13: Climate Action, Sustainable Development Goals. Retrieved March 4, 2021, from https://www.un.org/sustainabledevelopment/climate-change/

United Nations. (n.d.-b). Climate Change. Retrieved February 3, 2021, from https://www.un.org/en/sections/issues-depth/climate-change/

United Nations. (n.d.-c). The Paris Agreement. Retrieved May

Warnasooriya, R. and Sivananthawerl, T. (2016) KHAYA (Khaya senegalensis): IS IT A POTENTIAL PLANTATION FOREST SPECIES FOR CLIMATE CHANGE MITIGATION IN SRI LANKA? International *Journal of Agriculture, Forestry and Plantation*, 1, pp. 45-51.

Wei, Y., Zhao, M., Gao, J. (2024) What factors are influencing peri-urban forest carbon storage in different land use types based on permanent plots from 2009–2018, *Urban Ecosystems*, Doi: 10.1007/s11252-023-01461-6