



Estimation of Biomass Carbon Storage and Ecological Values of Urban Forest at Chulalongkorn University and its Implications for Carbon Management

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Abstract

Rapid urbanization and increasing greenhouse gas (GHG) emissions over recent decades have intensified climate change and air pollution. However, limited studies have quantified carbon storage and ecosystem services of tropical university campus forests using large-scale inventories and site-specific environmental data, particularly in Southeast Asian megacities such as Bangkok. This study aims to quantify biomass carbon storage and assess key ecosystem services of the urban forest at Chulalongkorn University (CU) and to evaluate their implications for campus-level carbon management. In this assessment, a total of 2,394 trees from a complete tree inventory collected in 2021 and 2022 were analyzed. Biomass carbon storage was estimated using both allometric equations and i-Tree Eco model as complementary approaches under different assumptions and to reflect potential variation between two methods for open-grown urban trees. In addition, the model was employed to evaluate major regulating ecosystem services, including carbon sequestration, air pollution removal, avoided stormwater runoff and oxygen production. To improve local representativeness of model inputs, site-specific hourly meteorological and air pollution data were incorporated. The results revealed that total biomass carbon storage was 1,914.47 tons (7,019.01 tCO_{2e}) based on manual calculations, whereas the i-Tree Eco model estimated a higher value of 2,796 tons. Furthermore, campus trees were found to sequester 97.81 tons of carbon annually and remove approximately 2.15 tons of air pollutants per year. They also contributed to stormwater management by reducing runoff by 6,460 m³ annually and produced about 260.8 tons of oxygen. Among all species, large and dominant trees in the study area, particularly *Albizia saman*, contributed the most to overall ecosystem services. The findings highlighted the role of urban forest in supporting carbon neutrality goals, tree conservation prioritization, green infrastructure planning and environmental management of the university, while demonstrating their broader value as nature-based solutions for climate mitigation and urban resilience.

Keywords : urban forest; i-Tree Eco; biomass carbon storage; carbon sequestration; ecosystem services

Introduction

Over recent decades, the combined effects of rapid urban expansion and greenhouse gas (GHG) emissions have become key drivers of global climate change. As a consequence, climate-related disasters have led to a fivefold rise in deaths over the past 50 years and displaced approximately 21.5 million people annually. In addition, air pollution has caused more than 7 million deaths each year worldwide [1]. In response to these challenges, forests play a critical role by improving environmental quality. They cover nearly one-third of the Earth's land area [2] and provide four major ecosystem services: provisioning, regulating, supporting, and cultural services [3]. Urban forests, which include all trees within cities and built environments, also offer similar benefits while delivering more immediate and direct impacts due to their proximity to dense populations [4].

However, the extent of urban forests in developing countries has been declining rapidly due to limited support and incentives. In Thailand, urban green spaces have also continued to decrease; however, university campuses still retain substantial tree cover [5]. In addition, universities are important urban carbon management units because they function as “small-scale cities” or “living laboratories,” where sustainability solutions can be tested before being scaled up to the municipal level. Their large physical footprints, high energy consumption, and roles as community hubs enable them to contribute significantly to emission reductions while educating future generations [5-7]. At the city scale, Bangkok has been facing urban heat island effects, air pollution, and flooding due to rapid urbanization, intensive anthropogenic emissions, and limited natural sink capacity. To address these interconnected challenges, standardized and locally grounded carbon assessment programs are needed to support evidence-based planning for urban greening [8, 9].

For effectively addressing climate change, Thailand has enhanced national targets for carbon neutrality and net-zero emissions by 2050 under its Nationally Determined Contributions (NDC 3.0). Within the Land Use, Land-Use Change and Forestry (LULUCF) sector, forests are expected to absorb about 118 million tons of CO₂ equivalent by 2035 [10]. At the institutional level, Chulalongkorn University (CU) has committed to achieving carbon neutrality by

2040 and net-zero emissions by 2050 [11]. For achieving these goals, CU launched the “Chula Race to Zero” initiative, which outlined five strategic approaches: energy transition, improving energy system resilience, creating green growth, lifestyle transition, and the social transition - social support system [5, 11-13]. However, the role of urban forests has not yet been clearly incorporated into the university's carbon neutrality strategies and sustainability reporting framework, despite the extensive tree cover across the campus. In particular, their contributions to carbon storage, a carbon sequestration, and other ecosystem services remain underrecognized. Therefore, localized assessment of the campus forest will provide valuable baseline information for university decision-makers to recognize and prioritize urban forests as an integrated component of future emission reduction policies and sustainability strategies.

At the global scale, carbon accounting and ecosystem service assessments have largely focused on natural forests; thus, benefits provided by urban forests have not been well understood [14]. Regional ecological assessments of urban forests have also been frequently carried out in cities across North America and Europe [15]. Such studies also still remain limited in Thailand, particularly at the university campus forest category. The first study using the i-Tree Eco model in Thailand was conducted by Intasen et al. (2017) to explore its feasibility within Bangkok urban area. Their study found that Bangkok had only 8.6% canopy cover, with trees collectively storing about 3.35 ton ha⁻¹ of carbon and annually sequestering about 0.176 ton ha⁻¹. However, the study could not calculate avoided runoff, PM_{2.5} removal and economic estimates of several ecosystem services [8]. In the second study, conducted at the Chulalongkorn University Centenary Park (CU100 Park) in 2019, park trees were estimated to store 7.84 ton ha⁻¹ of carbon, sequester 1.13 ton ha⁻¹ yr⁻¹, remove 0.14 ton ha⁻¹ of air pollutants annually, and mitigate 18.30 m³ ha⁻¹ of stormwater runoff per year. As the limitation, data from distant air pollution stations and default i-Tree Eco weather stations were used, which might reduce local representation of study site [16]. The third study analyzed regulating ecosystem services across 25 public parks in Bangkok and found that parks totally sequestered 800.7 tons of carbon, avoided 4726.6 m³ of runoff,

and removed 7.27 ton of air pollutants in 2020. However, only four air pollutants (CO , NO_2 , $\text{PM}_{2.5}$, PM_{10}) and limited tree parameters (species and diameter at breast height (DBH)) were used for the model's inputs [9]. In the current study, these limitations were addressed by improving data completeness and incorporating site-specific environmental datasets to enhance the local representativeness of model inputs. However, uncertainties associated with model assumptions, monitoring station distance, inventory quality, and parameter transferability were also acknowledged.

The term “urban forest” includes all trees in cities, towns and suburbs, including both private and public lands, from individual treet and yard trees to parks and wooded fragments [17]. In this study, the term “urban forest” encompasses all trees larger than 3.5 cm DBH within the CU campus, referred to as the “campus forest”. Although the i-Tree Eco model does not specify a mandatory minimum DBH threshold for tree inventories, this DBH range was selected with reference to Thailand's National Forest Inventory practices (2007) and previous urban forest studies that adopted comparable or slightly larger DBH criteria [16, 18]. In addition, while smaller trees currently contribute relatively lower ecosystem services, their inclusion remains important for representing future canopy expansion and long-term forest development. The objectives of this research are: (1) to quantify biomass carbon storage using both manual calculations and i-Tree Eco model; (2) to assess key regulating ecosystem services and their monetary values, including carbon sequestration, air pollution removal, avoided runoff, and oxygen production;

and (3) to evaluate implications of these ecosystem services for campus-level carbon management.

Methodology

Study Area and Period

The study area was the Chulalongkorn University (CU) in the central area of Bangkok, Thailand. For the whole campus, comprehensive complete tree inventory was conducted by the Faculty of Architecture during 2021 and 2022, as illustrated in **Figure 1**. The study area did not include the CU100 Park, Chulalongkorn University Demonstration School, the Faculty of Medicine and King Chulalongkorn Memorial Hospital, due to the data unavailability of the original inventory dataset. However, these exclusions were not expected to largely affect the overall representativeness of the assessment, as the inventory coverage of this study accounted for approximately 89.85 ha, representing 86.75% of the total campus area (103.57 ha).

Tree Inventory Data Description and Data Treatment

The original tree inventory dataset included a total of 2,660 trees with 21 dendrological and environmental parameters. During data collection, all trees with DBH of larger than 3.5 cm were measured; however, not all parameters were available for every tree, resulting in a final dataset of 2,394 trees for analysis after excluding incomplete records. As the inventory was conducted during the summers of 2021 and 2022, (191) trees measured in 2021 were adjusted to represent 2022

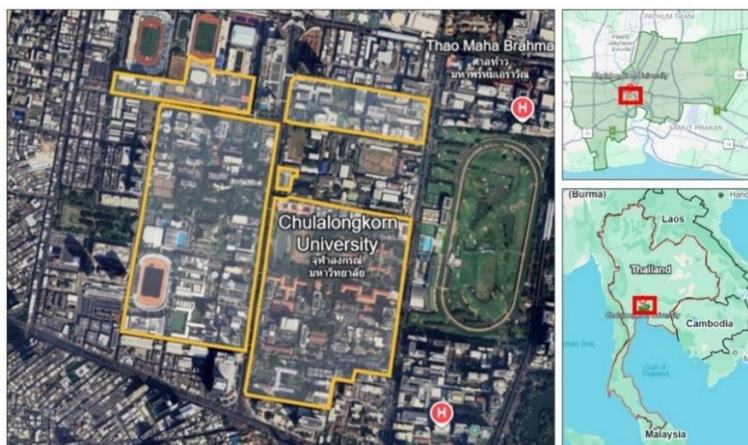


Figure 1 Study area and tree inventory coverage within Chulalongkorn University campus

conditions by adding mean annual growth increments for urban trees in Thailand (0.62 cm for DBH and 0.53 cm for tree height) [19]. These uniform increment values were applied to ensure consistency and because species-specific growth data for urban trees in Thailand are currently limited. Previous studies have also indicated that urban tree species in Bangkok generally exhibit relatively low interspecific variation in growth rates [5, 20, 21]. This adjustment resulted in only a minor change in the overall biomass estimation, with an increase of about 0.13% compared to the unadjusted one.

Manual Calculation of Carbon Storage

Tree biomass was manually estimated in three stages: (1) aboveground biomass (AGB) calculation, (2) belowground biomass (BGB) estimation, and (3) conversion of biomass into carbon storage. Initially, all trees were classified into two groups: evergreen (e.g., *Mimusops elengi*, *Ficus benjamina*, *Alstonia scholaris*) and deciduous species (e.g., *Albizia saman*, *Peltophorum pterocarpum*, *Lagerstroemia speciosa*). Evergreen species represented 47.12%, while deciduous species accounted for 52.88% of the total. This classification was based on published literature and botanical databases, including World Flora Online, e-Flora of Thailand, and Kew Gardens Plants of the World Online, etc. Different allometric equations were applied according to tree category for AGB estimation, and all calculations were performed using Microsoft Excel 2024. For evergreen species, a set of allometric equations developed by Terakunpisut et al. [22] was used to estimate biomass components, including stems, branches, and leaves (Equations 1-4). If the tree is deciduous species, equations of Ogawa et al. [23] were used and those equations were as described below (Equations 5-8):

$$WEs = 0.0509 \times (D^2 H)^{0.91} \quad (1)$$

$$WEb = 0.00893 \times (D^2 H)^{0.977} \quad (2)$$

$$WEl = 0.0140 \times (D^2 H)^{0.669} \quad (3)$$

$$AGBE = WEs + WEb + WEl \quad (4)$$

$$WDs = 0.0396 \times (D^2 H)^{0.9326} \quad (5)$$

$$WDb = 0.003487 \times (D^2 H)^{1.0270} \quad (6)$$

$$WDl = ((28.0 / (Ws + Wb) + 0.025)^{-1}) \quad (7)$$

$$AGBD = WDs + WDb + WDl \quad (8)$$

Where: WEs = mass of the evergreen tree stems (kg), WEb = mass of the evergreen tree branches (kg), WEl = mass of the evergreen tree leaves (kg), D = diameter at breast height of a tree (cm), H = height of a tree (m), AGBE = aboveground biomass of an evergreen tree species (kg), WDs = mass of the deciduous tree stems (kg), WDb = mass of the deciduous tree branches (kg), WDl = mass of the deciduous tree leaves (kg), and AGBD = aboveground biomass of a deciduous tree species (kg).

Total above-ground biomass (AGB) of both evergreen and deciduous tree species was obtained by summation of AGBE and AGBD [5]. Belowground biomass (BGB) was then estimated using the root-to-shoot ratio (R), calculated as a proportion of AGB. IPCC Guidelines for National Greenhouse Gas Inventories (2006) provides default R values for different climate zones and forest types. In this study, R-value of 0.24 was used because Bangkok is located in tropical latitudinal zone [24] and similar studies in Thailand also utilized this value [5]. Total biomass (TB) was calculated as the sum of AGB and BGB. Biomass carbon storage (TC) was then estimated by multiplying TB by a carbon fraction (CF) [25, 26]. A default CF value of 0.47 recommended by the IPCC for tropical and subtropical forests was employed in this study. Finally, carbon storage was converted into carbon dioxide equivalent (CO₂e) using a stoichiometric conversion factor of 3.6663 [5, 27].

Modeling of Ecosystem Services

For the estimation of ecosystem services provided by the CU campus forest, the i-Tree Eco model (version 6.0.39) was utilized. The assessment focused primarily on five regulating ecosystem services: biomass carbon storage, annual carbon sequestration, air pollution removal, avoided stormwater runoff and oxygen production. Air pollution removal was quantified for six pollutants: carbon monoxide (CO), nitrogen dioxide (NO₂), ozone (O₃), particulate matter with diameter ≤ 2.5 μm (PM_{2.5}), particulate matter with diameter between 2.5 and 10 μm (PM_{2.5-10}), and sulfur dioxide (SO₂). To achieve this, a comprehensive set of available tree inventory variables was incorporated in the model, as summarized in **Table 1**.

Table 1 Tree input variables used for ecosystem service estimation in i-Tree Eco

Category	Variable	Unit/Input	Description
Tree Identification	Tree species	-	Common name and scientific name of each tree species
Tree Structure	DBH	cm	Diameter of tree at breast height (1.3 m)
	Total height	m	Total tree height
	Live tree height	m	Height from the ground to live top of the tree
Crown Characteristics	Height to crown base	m	Height from ground to live crown base
	Crown widths	m	Width of the crown in two directions: North-South and East-West
	Crown light exposure (CLE)	0-5	Number of crown sides receiving sunlight (including overhead exposure)
	Crown dieback	%	Percentage of dead crown portion
	Crown missing	%	Missing crown volume compared to full crown
Site Field Information	Land use	Institutional	Land use type in which tree is located
	Strata	Urban	Sub-units by which study area are divided for analysis
	Street tree/ non-street tree	No	Identification if a tree is street tree (Yes) or not (No)
	Public/ private	No	Classification of tree as city managed (public (Yes)) or not (private (No))

Among the tree inputs, live tree height, crown light exposure (CLE), dieback and missing crown percentage, were not directly measured during the field inventory. Therefore, live crown height was assumed to be equal to total tree height because only a small proportion of campus trees exhibited top dieback, while dead branches were routinely pruned for safety management. In addition, CLE, dieback and missing crown percentage were retrospectively estimated through assessing photographs of each inventoried tree. Although this approach did not fully follow the standard field procedures recommended in the i-Tree Eco User Guide, the resulting canopy coverage estimates were generally consistent with values reported in the Campus Tree Plan and Heritage Tree Management of Chulalongkorn University (2024), which applied the i-Tree Canopy model to the same study area and period.

In addition to tree data, hourly precipitation and air pollution data of 2022 for six pollutants were compiled and formatted according to i-Tree submission requirements, and then submitted to the i-Tree database. Rainfall data was obtained from the King Chulalongkorn Memorial Hospital

station (located adjacent to the study site) upon request to the Pollution Control Department (PCD), Thailand. Air pollution data for five pollutants (excluding SO₂) were provided by Bangkok Metropolitan Administration (BMA) from the Ratchathewi District Office station, approximately 1.68 km north of the campus. Due to the unavailability of local SO₂ data, measurements from the Kasetsart University (KU) tower station, located about 12.86 km northeast of the study area, were used. All submitted datasets were validated by the i-Tree team, and subsequently integrated into the model. For meteorological inputs, hourly data for 2022, such as air temperature, solar radiation, wind speed, relative humidity, and atmospheric pressure, were chosen in the model from the nearest National Climatic Data Center station (ID: 484550-99999), located approximately 3.60 km east of the study site.

Air pollution removal in the i-Tree Eco was estimated based on the interaction among forest structure, local weather, and pollutant concentrations. The model calculated pollutant removal through dry deposition processes in which gaseous and particulate pollutants were absorbed or intercepted by tree

surfaces, particularly leaves. Field-measured tree parameters such as species, DBH, crown dimensions, crown condition, and leaf area were integrated with hourly weather and air-quality data to estimate the removal amount of pollutants by vegetation. According to the i-Tree methodology [28], pollutant flux was calculated using Equation 9:

$$F = V_d C \quad (9)$$

Where: F = pollutant flux ($\text{g/m}^2/\text{s}$), V_d = deposition velocity (m/s), and C = pollutant concentration (g/m^3).

The total mass of removed pollutants was subsequently aggregated across the total leaf area and modeled timeframe to estimate the annual pollution removal of the urban forest.

Results and Discussion

Biomass Carbon Storage and Annual Carbon Sequestration

Based on manual calculations with allometric equations, the total biomass (TB) of trees within the CU campus was estimated at 4,073.33 tons, comprising aboveground biomass (AGB) of 3,284.95 tons (80.65%) and belowground biomass (BGB) of 788.39 tons (19.35%). The total carbon (TC) stored in this biomass was estimated at 1,914.47 tons, equivalent to 7,019.01 tCO_{2e}. Detailed results are presented in **Figure 2**. This carbon estimate was higher than the 1,237.20 tons reported in a previous assessment of the same study site conducted in 2020 [5], although both studies used similar allometric equations and root-to-shoot ratio. The difference may be attributed to tree growth over time and differences in data acquisition methods, such as geoinformatics technology, Sentinel-2 satellite imagery, and aerial drone photographs in the previous study. In addition, the use of 2016 inventory data for validation may have further contributed to the lower carbon estimate compared with the present field-based inventory study.

For the modeling approach, the i-Tree Eco model generated both carbon storage and annual carbon sequestration, along with their monetary

values. Default economic parameters, including the U.S. EPA social cost of carbon [29] and an exchange rate of 1 USD = 32.68 THB, were applied due to the absence of locally derived ecological valuation data. The model estimated that trees in the CU campus stored a total of 2,796 tons of carbon (31.12 ton ha⁻¹ based on total campus area), equivalent to approximately 43.6 million THB. In contrast, manually estimated carbon storage was about 31.53% lower than this modeled result. This discrepancy might be due to allometric equations used in manual calculations which are often developed from natural forests or plantations, where lateral crown expansion is typically constrained [30]. Those equations may underestimate biomass components of urban context trees with larger crown area.

In addition, CU campus was dominated by species with naturally broad crown structures (**Table 2**), such as *Albizia saman* (rain tree or Chamchuri), *Pterocarpus indicus* (Burmese rosewood), *Peltophorum pterocarpum* (yellow flame tree), and *Terminalia catappa* (Indian almond). These species were not commonly represented in the forest stands used to develop the applied allometric equations. Consequently, the use of such generalized equations may have contributed to lower carbon estimates compared with the i-Tree Eco model, which applied species- or genus-specific equations and additionally incorporated crown variables into the estimation process. These differences may also be associated with root-to-shoot ratio selection, carbon fraction assumptions, and crown condition variables, which should be further evaluated in future assessments through sensitivity and uncertainty analyses.

Regarding species-level carbon storage patterns, *A. saman*, a widely cultivated non-native species in Thailand because of their high adaptability and favorable growth characteristics [31], contributed the largest share, accounting for 33.7% of the total (**Figure 3a**). This was likely due to its highest abundance across the campus as well as the relatively large size and age of many individuals. Then, *P. pterocarpum* (yellow flame tree) ranked second, followed by *P. indicus*, both of which are native to Thailand [32, 33].

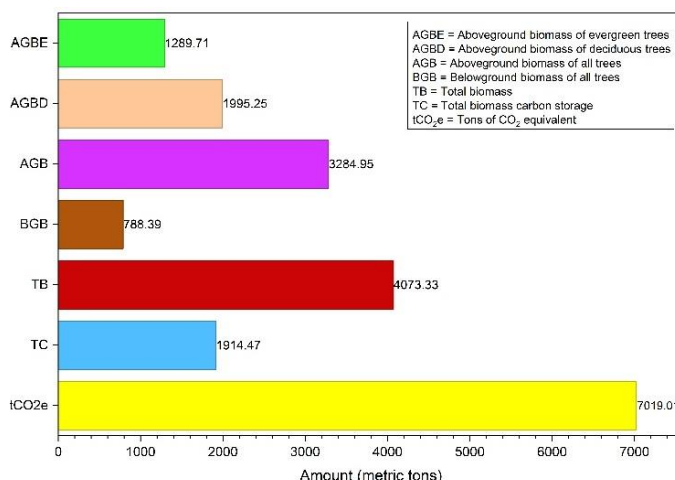


Figure 2 Manually calculated biomass carbon storage in CU urban forest

In terms of carbon sequestration, CU trees were estimated to absorb 97.81 tons of carbon annually, with an associated value of approximately 1.52 million THB per year. Similar to carbon storage, *A. saman* exhibited the highest sequestration capacity, contributing about 14.1% of the total annual carbon sequestration. This suggests that non-native can play a significant role in enhancing both carbon storage and sequestration, although their use should be carefully balanced. Then, *P. indicus* closely ranked second, and *P. pterocarpum* followed as third (**Figure 3b**). The similarity of annual carbon sequestration rates for *A. saman* and *P. indicus* might be due to the fact that many *A. saman* trees were old, affected by varying tree health conditions, and frequently pruned for groundwater conservation

and maintenance purposes, which may have reduced their annual growth and carbon uptake despite their large stored carbon reserves.

The carbon sequestration rate estimated in this study ($1.09 \text{ ton ha}^{-1} \text{ yr}^{-1}$) was very similar to that reported for CU100 Park in 2019 ($1.13 \text{ ton ha}^{-1} \text{ yr}^{-1}$) [16]. The similarity may reflect comparable urban conditions, climate characteristics, and tree growth performance across adjacent areas of the university landscape. In addition, both sites primarily consisted of managed urban green spaces, which likely supported similar levels of tree productivity and carbon uptake. This consistency may further indicate the reliability of carbon sequestration estimates for urban vegetation within the university environment.

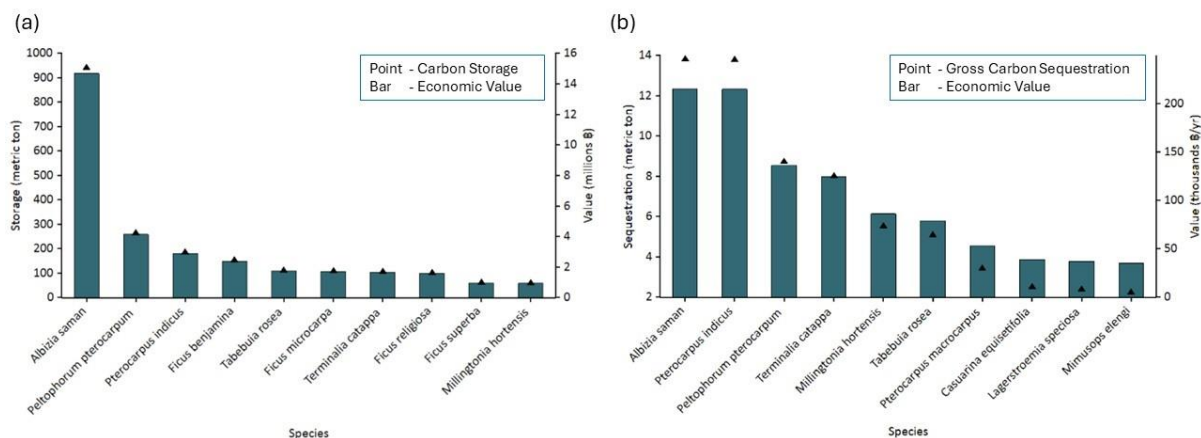


Figure 3 Carbon storage estimations and the associated economic valuation of CU urban forest (a) total carbon storage and (b) annual carbon sequestration

From management perspective, campus carbon-related ecosystem functions were found to depend strongly on a few dominant tree species. However, such excessive reliance could increase vulnerability to pests, diseases, storm damage, and future climate-related stress [28]. Therefore, management strategies should not focus solely on maximizing ecosystem-service outputs, but also on improving long-term

ecological resilience through species diversification. Protecting large mature trees of high-performing species while gradually supplementing future plantings with a broader mixture of native and climate-tolerant species could help maintain ecosystem stability. Suggested management implications of the 10 most common species for future planting strategies are presented in **Table 2**.

Table 2 Carbon contribution and management implications of top 10 dominant campus tree species in CU

Species	Population Percent	Mean DBH (cm)	Carbon Storage (ton)	Carbon Sequestration (ton yr ⁻¹)	Origin Status	Management Implication
<i>Albizia saman</i>	16.8	78.06	941.91	13.81	Exotic	Very high carbon storage and large canopy benefits; maintain mature trees but avoid excessive planting in the future for increasing species diversity
<i>Pterocarpus indicus</i>	12.7	38.72	185.25	13.81	Native	High carbon sequestration and valuable native species; prioritize protection and future planting
<i>Peltophorum pterocarpum</i>	6.9	65.45	265.34	8.73	Native	Good ecosystem-service contribution and shade provision [34]; suitable for continued but balanced planting
<i>Tabebuia rosea</i>	6.8	47.53	111.23	5.08	Exotic	Moderate carbon contribution with ornamental and drought tolerant values [35]; suitable as a supplementary species rather than dominant planting
<i>Pterocarpus macrocarpus</i>	4.0	37.67	59.69	3.41	Native	Native species with good long-term carbon storage potential; suitable for expanded planting
<i>Terminalia catappa</i>	4.0	51.82	106.30	8.01	Native	High canopy [36] and carbon benefits with strong climate resilience; recommended for continued planting in suitable areas
<i>Terminalia ivorensis</i>	3.1	34.23	24.17	1.75	Exotic	Lower carbon contribution despite moderate abundance; future planting should be limited to maintain species balance
<i>Millingtonia hortensis</i>	3.0	33.64	59.81	5.52	Native	Moderate ecosystem-service contribution; useful for increasing species diversity in urban landscapes
<i>Mimusops elengi</i>	2.7	34.62	28.94	2.25	Native	Native evergreen species with moderate ecosystem benefits; suitable for diversified and resilient planting
<i>Lagerstroemia speciosa</i>	2.1	35.22	25.11	2.39	Native	Native ornamental species with moderate carbon benefits; suitable for enhancing species diversity and landscape value

Regarding institutional carbon goals, the estimated carbon storage and sequestration demonstrated that the campus urban forest contributed directly to GHGs mitigation to some extents. CU reported total GHGs emissions of 49,755 tCO₂eq during the 2022 - 2023 academic year [12]. Based on the results of this study, campus trees annually sequestered 97.81 tons of carbon (358.64 tCO₂eq) representing about 0.72% of the total emissions. Although this contribution was relatively small, the potential role of campus forests in providing additional nature-based ecosystem services beyond carbon benefits should not be overlooked. These findings also suggested the need to establish suitable forest-based emission reduction targets and to consider campus forest as a component alongside the current five key strategies under the “Chula Race to Zero” initiative. Such efforts could prioritize the conservation and expansion of campus tree cover to enhance carbon stocks and ecosystem benefits.

Air Pollution Removal and Stormwater Runoff Reduction

The results indicated that CU trees removed approximately 2.15 metric tons of air pollutants (here: 1000 kg = 1 metric ton), with an associated economic value of about 728,000 THB (**Figure 4a**). Among the pollutants, O₃ removal was highest, amounting to 0.712 tons per year (292,167.8 THB), followed by PM_{2.5-10} at 0.619 tons per year (169,611 THB). NO₂ ranked third, with 0.574 tons removed annually, corresponding to an economic value of 235,634 THB. Then, CO, PM_{2.5}, and SO₂ followed, with removal amounts of 0.135, 0.066, and 0.057 tons per year, respectively. In this study, SO₂ data may not have fully represented conditions within the study area because they were obtained from a far station. However, since pollutant removal was calculated separately for SO₂ in the model [28], this limitation likely affected only the accuracy of the SO₂ estimates rather than the overall calculation of other pollutants.

The findings of pollution removal can be explained by the pollutant removal mechanisms of trees. Trees remove gaseous pollutants such as CO, NO₂, O₃, and SO₂ primarily through

stomatal uptake and absorption by leaf surfaces [37], whereas particulate matter (PM_{2.5} and PM_{2.5-10}) is captured through deposition onto leaf surfaces [38]. Among these pollutants, ozone and nitrogen dioxide are generally removed more efficiently due to their higher reactivity and stronger interaction with leaf physiological processes, while particulate matter removal is influenced by leaf surface characteristics and environmental factors [39]. In contrast, carbon monoxide exhibits relatively low removal efficiency due to its weak interaction with plant surfaces [38]. This pattern is consistent with the results presented in **Figure 4a**.

According to the study by Intasen et al., the annual air pollution removal in Bangkok in 2013 was estimated at 0.008 ton ha⁻¹ [8], which was substantially lower than the value obtained in the present study (0.024 ton ha⁻¹). This difference was likely associated with lower tree canopy cover and smaller tree diameter sizes within the broader urban area of Bangkok compared with the well-managed and mature urban forest of the university campus. However, the estimated value in this study was more comparable to the average pollution removal reported for 25 parks in Bangkok (0.031 ton ha⁻¹) [9], possibly due to the greater canopy cover and larger DBH of urban park vegetation relative to the earlier citywide assessment.

For the avoided runoff estimation, i-Tree Eco estimated based on rainfall interception by tree canopies [28]. Although various tree components (leaves, branches, and bark) can intercept rainfall, the model considers only interception by leaves. The economic value of avoided runoff was estimated using values from the U.S. Forest Service's Community Tree Guide Series, with a unit value of 77.16 THB/m³ applied in this study due to the lack of local data [40]. The results showed that CU campus trees reduced surface runoff by approximately 6,460 m³ per year, corresponding to an indicative economic value of about 500,000 THB. The same pattern to carbon sequestration was observed for the top three contributing tree species to avoided runoff (**Figure 4b**) because of the most dominant species across the campus.

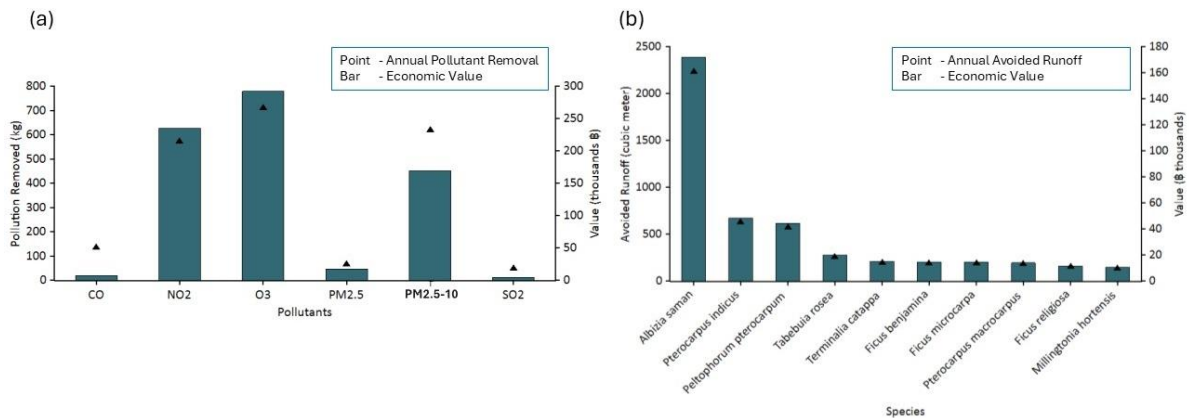


Figure 4 Key ecosystem services of CU urban forest
(a) annual pollution removal and (b) avoided runoff and their associated economic values

The study area covered approximately 103.57 ha, of which nearly 60% consisted of impervious surfaces such as roads, buildings, and pavements. During the 2022 study period, annual rainfall reached approximately 2,378 mm, representing substantial rainfall input to the campus hydrological system. Under these conditions, the presence of urban trees contributed to stormwater regulation by reducing runoff volume by up to 71.89 m³ ha⁻¹, thereby helping to reduce pressure on drainage infrastructure. However, the actual runoff reduction could vary depending on annual rainfall patterns and climatic conditions. In comparison, the avoided runoff provided by trees in 25 parks in Bangkok showed lower average value (22.94 m³ ha⁻¹) [9], possibly due to differences in leaf area and lower annual rainfall during the study period. An earlier study of Bangkok urban area reported an even lower runoff interception value (~ 0.75 m³ ha⁻¹) [8], likely due to substantially lower tree cover and smaller tree sizes.

Oxygen Production by Urban Trees

In the i-Tree Eco model, oxygen production by urban trees is estimated based on carbon sequestration using a stoichiometric conversion factor (32/12). For complete inventory datasets such as this study, oxygen production is calculated from gross carbon sequestration without accounting for decomposition, resulting in slightly higher estimates. As the result, CU campus trees were estimated to produce approximately 260.8 metric tons of oxygen per

year, with the same top ten contributing tree species presented in **Figure 3b**. Among these, *A. saman* (36.82 ton yr⁻¹), *P. indicus* (36.81 ton yr⁻¹), and *P. pterocarpum* (23.29 ton yr⁻¹) were the highest contributors, largely due to their dominance across the campus and their relatively large sizes, which enhance carbon uptake and oxygen release.

However, the economic valuation of oxygen production was excluded in the model because atmospheric oxygen is abundant and its monetary significance is considered limited [28]. In addition, the economic values of ecosystem services in this study should be interpreted as indicative estimates rather than precise locally validated ones because local economic data were largely unavailable; therefore, the model primarily applied U.S.-based valuation coefficients. Consequently, the direct transferability of these economic parameters to the Thai socio-economic context may be limited. Nevertheless, the valuation results remained useful for illustrating the relative magnitude and planning relevance of ecosystem services. For example, the estimated carbon-related benefits were generally comparable with emerging carbon pricing mechanisms and voluntary carbon markets in Thailand.

Conclusions

This study quantified the biomass carbon storage and ecosystem services provided by the CU urban forest using manual method and

i-Tree Eco. The results consistently demonstrated that a few dominant species, particularly *A. saman*, *P. indicus*, and *P. pterocarpum*, contributed substantially to ecosystem services provision across the campus. However, long-term urban forest management should balance between ecosystem-service performance and ecological resilience, by conserving large mature trees while gradually increasing species diversity through future plantings of native and climate-tolerant species. In addition, maintaining healthy crown condition and adequate growing space are essential for sustaining ecosystem functions.

In addition, the existing carbon storage represented the total amount of carbon currently stored within campus forest, whereas annual carbon sequestration reflected the yearly uptake of atmospheric carbon. Although these ecosystem services contributed to the university's carbon neutrality goals, campus forests should be considered as complementary nature-based solutions that support, but do not replace, direct GHGs emission reductions in the energy, transportation, and waste sectors. Moreover, the reported estimates should be interpreted as inventory-based and model-based assessments subject to uncertainty associated with common equations, fixed root-to-shoot ratios, default carbon fractions, monetary valuation coefficients, excluded campus areas, and spatial variability in weather and air pollution data. Consequently, the precision of the estimated values may be influenced by assumptions embedded within the applied equations, parameters, monitoring stations and valuation approaches.

To enhance robustness and practical applicability, further research should incorporate local monetary data, uncertainty and sensitivity analyses, DBH-class assessment, spatial distribution analysis of ecosystem services, long-term canopy monitoring, improved manual calculations based on species-specific equations, and expanded spatial coverage. Integrating ecosystem-service assessment with CU's annual greenhouse gas inventory could further strengthen campus sustainability planning and green infrastructure investment. Overall, the study underscored the role of urban forests as effective nature-based solutions (NBS) for

climate change mitigation, air quality improvement, and urban resilience. At a broader scale, the outcomes of this research may support urban environmental policy development and green infrastructure planning in cities seeking sustainable and climate-resilient solutions.

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