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Article

Carbon sequestration analysis of the university campuses in the Bangkok Metropolitan Region

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Abstract: Due to the gradual growth of urbanization in cities, urban forests can play an essential role in sequestering atmospheric carbon, trapping pollution, and providing recreational spaces and ecosystem services. However, in many developing countries, the areas of urban forests have sharply been declining due to the lack of conservation incentives. While many green city spaces have been on the decline in Thailand, most university campuses are primarily covered by trees and have been serving as urban forests. In this study, the carbon sequestration of the university campuses in the Bangkok Metropolitan Region was analyzed using geoinformatics technology, Sentinal-2 satellite data, and aerial drone photos. Seventeen campuses were selected as study areas, and the dendrometric parameters in the tree databases of two areas at Chulalongkorn University and Thammasat University were used for validation. The results showed that the weight average carbon stock density of the selected university campuses is 46.77 tons per hectare and that the total carbon stock and sequestration of the study area are 22,546.97 tons and 1402.78 tons per year, respectively. Many universities in Thailand have joined the Green University Initiative (UI) and UI GreenMetric ranking and have implemented several campus improvements while focusing on environmental concerns. Overall, the used methods in this study can be useful for university leaders and policymakers to obtain empirical evidence for developing carbon storage solutions and campus development strategies to realize green universities and urban sustainability.

Keywords: carbon sequestration; university campus; urban forest; sustainability; Bangkok Metropolitan Region

1. Introduction

Climate change has raised global awareness of reducing greenhouse gas (GHG) emissions. This environmental problem fostered the international negotiation and cooperation of the United Nations Framework Convention on Climate Change (UNFCCC) in 1992 and the Kyoto Protocol in 1997 (De Villiers et al., 2014). According to the detailed specification of GHG in UNFCCC, the units of GHG emissions can be converted into equivalent CO_2 units (Wattanakuljarus, 2012). In addition, the Paris Agreement set long-term temperature goals of holding the global average temperature increase to well below 2 °C and pursuing efforts to limit the increase to 1.5 °C, thus urgently calling for "zero global GHG emissions" (Schleussner et al., 2016). With the guidance of international initiatives, many countries have been making joint efforts to reduce their GHG emissions, i.e., intended nationally determined contributions (Heo et al., 2019). For instance, the European Union initiated an emissions trading scheme for entities to offset their emission liabilities, and thus a new "carbon economy" was created (De Villiers et al., 2014).

Urban forests are the assemblage of vegetation and soils in complex urban systems, in which humans are the main drivers of forest structures (Escobedo et al., 2011; McPherson et al., 1994; Ward and Johnson, 2007). Urban forest structures, such as urban green spaces, tree densities, and tree species composition, are mainly subjected to the influences of urban ecology (Bekisoglu and Keyis, 2023). Urban forests are unique and highly valued resources, and they play a significant role in environmental quality and human well-being. Trees are essential for urban forests, providing essential ecosystem services, such as ambient temperature reduction, biodiversity protection, and air pollution removal (McPherson et al., 1994; Nowak and Crane, 2002). Moreover, through energy conservation from properly located trees, urban trees contribute to carbon dioxide reduction through direct carbon storage and the avoidance of CO_2 production by fossil-fuel power plants. On the one hand, urban trees can act as carbon sinks by fixing carbon during photosynthesis and storing excess carbon as biomass (Jaman et al., 2016; Nowak and Crane, 2002). Also, urban trees can affect local climates through temperature reduction, consequently reducing energy use in buildings and power plants' emissions (McPherson et al., 1994; Nowak and Crane, 2002).

Universities are important for many societies worldwide, providing life-long education opportunities (Qian and Yang, 2018). Since universities have many facilities and people that consume a lot of energy, university campuses can be considered small-scale models of entire cities (Guerrieri et al., 2019). "Greening" of university campuses can represent sustainability practices in higher educational institutions, and it is defined as the process of reducing the multitude of the on- and off-site environmental impacts caused by campus decisions and activities (Dahle and Neumayer, 2001).

Green campuses can produce multiple benefits. First and foremost, universities can enlarge the effects of environmental protection on the public due to their teaching, research, and policy development experiences (Dahle and Neumayer, 2001). Second, green campuses can improve the image of many universities, leading to the competitive advantage of environmental friendliness and thus attracting more students and staff (De Villiers et al., 2014). Third, previous studies have shown that green space can positively benefit students' academic performances (Rahai et al., 2023). Therefore, addressing the benefits of greening campuses can encourage universities to voluntarily undertake sustainability initiatives.

In addition, the Green University Initiative (UI) is among the initiatives for creating urban forests in cities. The UI GreenMetric World University Ranking, which was launched in 2010, is one of the university ranking programs focusing on the current conditions and policies related to Green Campuses and Sustainability in universities worldwide, and it is expected to draw the attention of university leaders and the public on the environment and global climate change. Many universities worldwide, Thailand included, have been involved with the ranking. For example, in

2021, Kasetsart University was ranked the best green university in Thailand and the 45th green university globally. The second-best green university in Thailand is Mahidol University, and it ranks 59th globally (UI Green Metric, 2021). In 2023, Chulalongkorn University (CU) has pledged to be the "university with net zero greenhouse gas emissions" by 2050 (Chulalongkorn University, 2023). As part of the global initiative towards Net Zero Emissions, Chulalongkorn University is taking various measures to reduce its carbon footprint. However, not much has been done to examine the role of university campuses and their contributions to carbon reduction.

This study focuses on the carbon sequestration analysis of university campuses. Geoinformatics technology and remote sensing data were used to calculate the performance of urban forests on university campuses in terms of the reduction of carbon emissions in the Bangkok Metropolitan Region (BMR). This study is one of the first to analyze the carbon sequestration of the university campuses in the BMR. The study areas of Chulalongkorn University and Thammasat University (TU) were used as case studies to develop a ground-truth database.

The advancement of the methodological framework of carbon stock analyses is expected to expand in green space areas, such as public parks, residential areas, and university campuses. In addition to its academic contribution, this research aims to shed some light on the significance of urban and university forests, which can be counted as forest areas based on UNFCCC guidelines.

1.1. Carbon stock, storage, and sequestration

Carbon stock is defined as the quantity of the net carbon content of plants in a particular area or volume at a specified time, and its measurement unit is mass (Bindu et al., 2020; Karsenty et al., 2003). However, carbon storage and sequestration are the processes of capturing and storing atmospheric CO_2 (Sedjo and Sohngen, 2012). There, carbon sequestration can indicate the changes in carbon storage over time. Generally, CO_2 can be sequestered through three methods: geological storage, ocean storage, and biotic sequestration. Biotic sequestration, a natural process, is considered a sustainable method for removing CO_2 from the atmosphere using microorganisms, soil organic matter, and photosynthesis plants (De Villiers et al., 2014; Eloka-Eboka et al., 2020). This involves fewer concerns regarding the detrimental effects on the environment and the vast costs of equipment and technology compared to the other two methods (Lal, 2008).

1.2. Carbon stock assessment

By better understanding urban ecosystems, developing management plans and policies that can significantly improve both environmental quality and human well-being can be facilitated (Nowak and Crane, 2002). Specifically, the carbon stock assessment of urban forests can help monitor their dynamics and investigate their structures and conditions, thus facilitating carbon storage and sequestration quantification. For example, Myeong et al. (2006) showed that the carbon storage of urban forests in Syracuse, New York is variable over time, with 46,800 tons of carbon in 1985; 149,430 tons in 1992; and 148,660 tons in 1999. Predicting the future carbon storage and sequestration of trees is also essential; long-standing trees can store long-term carbon as wood products or landfills or emit carbon back into the atmosphere via fossil-fuel combustion (Nowak and Crane, 2002).

In addition, the structures and conditions of forests are significant factors that influence the carbon stocks of trees. The carbon per unit of tree cover varies among US cities because of variations in tree density, tree sizes, and species composition (Nowak and Crane, 2002). In addition, tree diversity and basal areas positively correlate with carbon stocks (Jaman et al., 2020). Moreover, tree conditions, such as growth rate and age, have specific impacts on biomass growth and carbon accumulation capacity (Köhl et al., 2017). Overall, various factors in complex urban systems affect urban forests' carbon storage and sequestration.

In the context of climate change and urbanization, properly planning and managing urban forests can improve urban environments and help potentially store significant amounts of carbon (Delphin et al., 2016; Liu and Li, 2012). For example, enhanced urban forest management in Nepal can increase carbon sequestration in community forests to between 10 and 33 tons per hectare over three years (Shrestha et al., 2014). The insights on how the carbon stocks of trees are affected can have planning and management implications. Moreover, the comprehensive consideration of tree diversification, specific sites, tree density, tree conservation, and other forest structure parameters can substantially enhance carbon storage and thus produce more extensive carbon benefits for carbon–climate feedback (Jaman et al., 2020).

The required sequestration and carbon storage capacities to offset the anthropogenic CO_2 emissions generated by cities can be limited. Tang et al. (2016) quantified the carbon storage and carbon sequestration rates of urban streets and found that urban street trees have relatively limited roles in offsetting the overall anthropogenic CO_2 emissions through carbon sequestration. This result indicates that only the carbon sequestration by street trees is insufficient for offsetting CO_2 emissions. The same results can also be observed in urban parks located in Bangkok (Fujimoto et al., 2016). Additional measures are needed for the joint formatting of a CO_2 mitigation mechanism. Therefore, the timely, consistent, and accurate quantification of carbon stocks in vegetation in cities is critical to improving our understanding of the role of urban green spaces in guaranteeing urban carbon balance (Tang et al., 2016). Thus, to ensure the effectiveness of urban forests as GHG mitigation measures, investigating the current forest structural parameters of urban forests and assessing the capacity and potential of carbon storage are needed.

1.3. Methods and tools for the calculation of carbon stocks

The carbon stock assessment by urban forests involves two major steps: collecting a forest's inventory data and estimating the biomass of its trees (Bindu et al., 2020; McPherson et al., 1994; Nowak and Crane, 2002; Tang et al., 2016). Collecting the structure parameters and characteristics of a forest through field surveys is a prerequisite for carbon-related calculations at multiple levels, such as location, tree height, diameter at the breast (DBH), canopy condition, tree density, and species composition (De Villiers et al., 2014; Nowak and Crane, 2002). As for biomass estimation, it can be calculated using allometric equations. For example, by using allometric equations developed from an empirical study on dryland forests, Jaman et al. (2016) estimated the aboveground biomass of individual trees for different urban land uses in Dhaka city, Bangladesh. Tang et al. (2016) applied species-specific, genus-specific, and generalized equations to calculate the dry biomass of urban street trees. After measuring forest structure parameters and tree biomass, carbon or carbon dioxide contents could be calculated using conversion factors. Some works applied species-specific methods (Nowak and Crane, 2002), while others used average parameters across species (De Villiers et al., 2014). For example, the dry biomass content can be converted into carbon content by multiplying by 0.5 (Tang et al., 2016). Then, the CO_2 amount can be calculated by multiplying the carbon amount by 3.6663, as two oxygen molecules are added to each carbon molecule. In addition, to calculate the current CO_2 stock, the future CO_2 sequestration can be estimated based on the tree growth rate (De Villiers et al., 2014).

Field data has been used to extrapolate entire areas for large-scale estimations. For example, Tang et al. (2016) demonstrated the calculation of the carbon storage of 2040 trees in 204 roads in Beijing by the extrapolation of the total area of urban districts, and Nowak and Crane (2002) used the carbon data in 10 US cities to extrapolate the whole nation. However, such intensive field investigations have several limitations. First, acquiring data from each tree is a time-consuming task requiring much staffing (Heo et al., 2019). Second, manual measurements can result in inaccurate data. Moreover, larger areas and more sample sites are needed to improve the estimation accuracy of extrapolation (Tang et al., 2016). Thus, rapid, accurate, and automated retrievals of forest parameters are needed to tackle the abovementioned limitations.

The rapid development of geospatial technologies, such as remote sensing, Light Detection and Ranging (LiDAR), and cloud computing platforms, e.g., Google Earth Engine, has led to great potential with regard to monitoring and assessing the dynamics of forests, including carbon storage and sequestration (Bindu et al., 2020). Since the 1990s, the use of fine-resolution remote sensing and LiDAR, combined with ground observation data and modeling, has received considerable research attention, such as in the fields of carbon storage assessments and sequestration (Tang et al., 2016; Wallace et al., 2012). When used with automatic data processing techniques, LiDAR makes forest parameter extraction less time-consuming and relatively accurate (Huang et al., 2015). Recently, the development of unmanned aerial vehicles (UAVs) has resulted in alternative remote sensing platforms. Moreover, UAV-borne LiDAR has significant potential in forestry research, as it permits extensive and accurate area coverage, thus tackling the limitations of time consumption, inaccurate data, and insufficient sample sites (Wallace et al., 2012).

1.4. Carbon stock assessment of university campuses

Common climate change concerns worldwide have led to green campus initiatives in universities with regard to carbon management and accounting (Hooi et al., 2012). The capability and potential of carbon storage and sequestration by trees in university campuses have received considerable research interest, as university campuses are individual organizations with their own green areas. In a university campus in New Zealand, 4137 trees are estimated to store 5809.4 tons of CO_2, and 253 tons of CO_2 are expected to be sequestered per annum over the next ten years (De Villiers et al., 2014). At California State University, Northridge, the assessment results showed that the annual carbon sequestration of individual trees ranges from 25 kg to 550 kg per year (Cox, 2012). In the UK, universities set up management plans with assistance from the Higher Education Carbon Management Programme (Mazhar et al., 2019). These practices prove that universities can play influential roles in CO_2 mitigation mechanisms.

Carbon stock assessments on campuses can provide lessons and implications beyond universities (De Villiers et al., 2014). Universities have a significant role to play in promoting and scaling up sustainability practices due to their wide influence as knowledge hubs in cities. However, compared to other urban functional land uses, such as urban streets and parks, there is a lack of research on the carbon stocks of trees in universities. This lack of data limits the support for green campus initiatives and carbon mitigation efforts. Though the empirical studies on specific universities show the capability and potential of carbon stocks by trees, the information provided from the results is still insufficient to institutionalize relevant carbon management programs. In other words, the differences and similarities of carbon stocks among universities, which can help identify good practices and have significant implications for green campus planning and carbon management, are still under exploration. Therefore, a comprehensive carbon stock assessment is needed to evaluate the carbon storage and sequestration by trees on a large scale.

To address this gap, accurate, rapid, and large-scale carbon stock assessments focusing on multiple universities are needed. Recent developments in UAV-LiDAR and cloud computing platforms such as Google Earth Engine (GEE) provide opportunities for overcoming this challenge. Drones and LiDAR can be used to collect forest structure parameters, including tree height and DBH, from the point cloud, which can contribute to assessing the carbon stocks of trees. Additionally, GEE can help in the effective extraction of forest areas on all campuses. This combination of technologies can provide more comprehensive and accurate data on urban forest carbon storage and sequestration in universities.

Previous studies have only focused on individual universities, either to test the accuracy of tree parameter measurement with LiDAR or to calculate the carbon stocks of trees through intensive manual field measurements. Therefore, assessments on multiple university campuses are essential to provide reliable and sufficient information regarding the differences and commonalities among universities. This data can be used to identify good practices, facilitate knowledge exchanges and cross-university partnerships, and comprehensively develop and improve the carbon management of higher education institutions.

2. Materials and methods

2.1. Study area

Thailand has witnessed a radical increase in the CO_2 outflow in tons per capita (Muhd Nor et al., 2016). For example, from 1985 to 2005, Thailand's annual increment rate of GHG emissions (9.15%) was much higher than its average annual economic growth rate of 6.05%. Moreover, the average annual growth of GHG emissions in

Thailand was also higher than that in the Association of South East Asian Nations or ASEAN (7.06%), Asia (5.00%), and the world (2.34%) (Wattanakuljarus, 2012). The high GHG emissions in Thailand imply that urgent actions need to be taken to reduce GHG emissions and reverse the adverse trend. Currently, the government of Thailand is developing measures and mechanisms to support GHG reduction in all sectors (Office of the National Economic and Social Development Board, 2017). As CO_2 is a dominant GHG, carbon sequestration by trees is one of the methods advocated by international initiatives to offset carbon emissions from anthropogenic emissions (Nowak and Crane, 2000; Sedjo and Sohngen, 2012).

Bangkok is the capital and largest city in Thailand and one of the major global metropolitan regions in Southeast Asia, and the intensive anthropogenic activities in Bangkok have led to a large amount of GHG emissions. In this regard, the Bangkok Metropolitan Administration (BMA) and Japan International Cooperation Agency (JICA) have made efforts to reduce GHG emissions through the Bangkok Action Plan on Global Warming 2007–2012 and further initiated the Bangkok Master Plan on Climate Change 2013–2023 (BMA and JICA, 2015). In general, mitigation measures in the green urban planning sector are essential components of this Master Plan. In general, this plan is expected to reduce or absorb 49,279 tons of carbon dioxide equivalent (CO_2e) in this sector in 2020 through mitigation actions, such as establishing new public parks, increasing new green areas in public areas, planting new trees in roadside areas, increasing the Biotope Area Factor in private lands, and mangrove reforestation. However, to achieve these targets, it is necessary to identify the roles and responsibilities of stakeholders, develop a feasible implementation schedule, and conduct efficient and accurate assessments of CO_2 absorption (BMA and JICA, 2015).

The urbanization of Bangkok has extended to the provinces around it (Anantsuksomsri and Tontisirin, 2015). The socioeconomic activities of the capital city are connected with the surrounding cities in the BMR, which covers an area of approximately 7700 square kilometers and includes six provinces: Bangkok, Nakhon Pathom, Nonthaburi, Pathum Thani, Samut Prakan, and Samut Sakhon. People in Bangkok commute to go to their workplaces, schools, and universities. In the BMR, 73 universities (102 university campuses) are registered with the Ministry of Higher Education, Science, Research, and Innovation (MHESRI, 2018). **Figure 1** shows the locations of the university campuses in the BMR. In this study, we focused on urban campuses with a total area of over 10 hectares. These criteria represent the potential of green university campuses, urban forest development, and the economies of scale for carbon sequestration. Based on the criteria, 17 campuses were selected (**Table 1**).

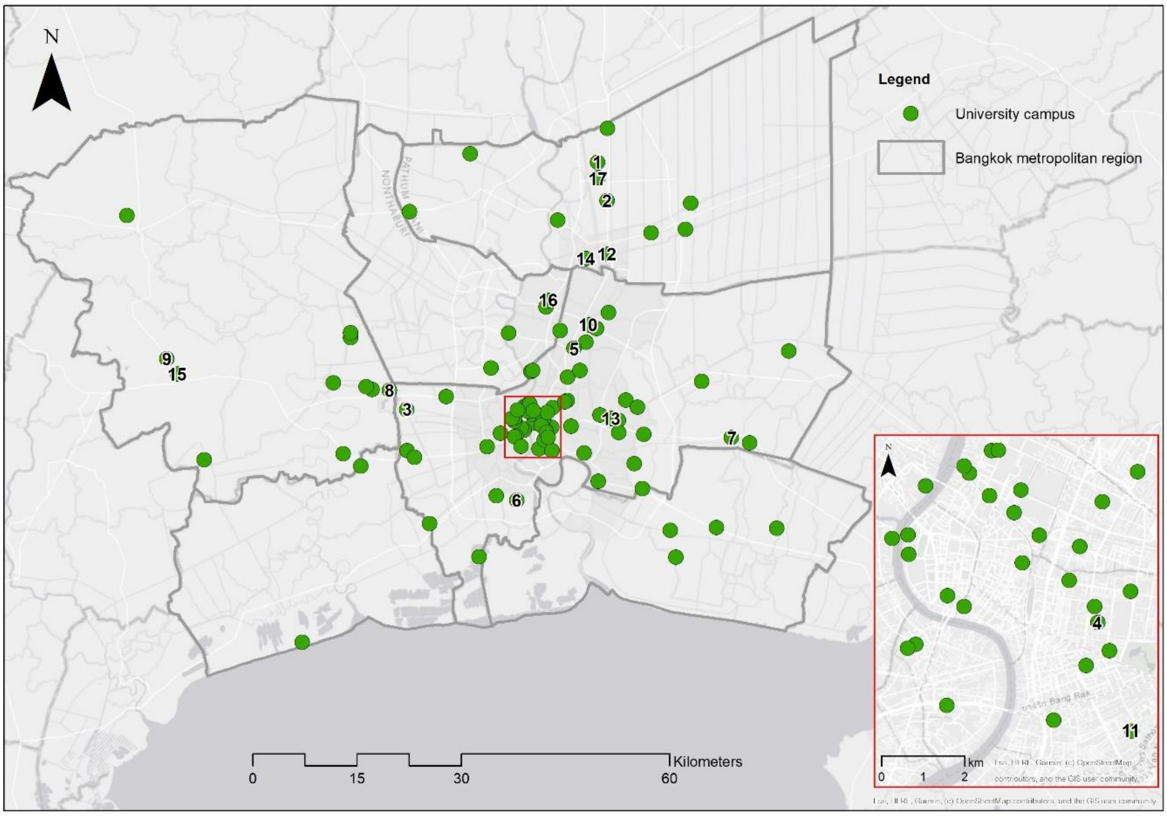


Figure 1. Locations of the university campuses in the BMR and selected campuses. Source: Authors.

Table 1. Selected campuses for forest cover mapping and carbon sequestration accounting.

ID	University	University Area (ha)	Tree Cover Area (ha)	Tree Cover (%)
1	Asian Institute of Technology	99.89	73.81	73.9%
2	Bangkok University	62.73	23.89	38.1%
3	Bangkokthonburi University	27.20	4.11	15.1%
4	Chulalongkorn University	103.57	31.08	30.0%
5	Kasetsart University	140.62	44.83	31.9%
6	King Mongkut's Institute of Technology Ladkabang	99.15	30.74	31.0%
7	King Mongkut's University of Technology Thonburi	21.65	4.09	18.9%
8	Mahidol University	170.76	83.62	49.0%
9	Nakhon Pathom Rajabhat University	36.03	15.15	42.1%
10	Phranakhon Rajabhat University	26.31	7.34	27.9%
11	Rajamangala University of Technology Krungthep	21.15	6.63	31.4%
12	Rajamangala University of Technology Thanyaburi	18.53	7.17	38.7%
13	Ramkhamhaeng University	48.97	8.60	17.6%
14	Rangsit University	38.78	8.24	21.3%
15	Silpakorn University Sanam Chandra Palace Campus	62.60	33.68	53.8%
16	Sukhothai Thammathirat University	22.18	5.34	24.1%
17	Thammasat University Rangsit Campus	257.52	93.71	36.4%

The street tree species in Bangkok are quite similar and limited in number. According to Thaiutsa et al. (2008), the most frequently found tree species in Bangkok are Pterocarpus indicus, Tabebuia rosea, and Cassia fistula, which make up more than 50% of the total number of trees that were surveyed. It is estimated that only 8.6% of the total area of Bangkok is covered by tree canopy (Intasen et al., 2017). However, most university campuses in the Bangkok Metropolitan Region (BMR) are primarily covered by trees or green areas. These campuses, which can be considered urban forests, have played increasingly essential roles in sequestering atmospheric carbon, trapping air pollution, reducing heating and cooling costs, and providing recreational spaces and other ecosystem services in the city.

In addition to the main selection criteria, Chulalongkorn University and Thammasat University campuses were selected for drone mapping assessments based on their ratios of green spaces and green campus initiatives (**Figure 2**). As two of the most prestigious universities in Thailand, they have attached importance to green campus actions that address environmental protection through various aspects, such as increasing green spaces, encouraging public transportation, sustainable waste management, and renewable energy utilization.

Founded in 1917, Chulalongkorn University occupies 103.57 hectares in the center of Bangkok, and it is the oldest university in Thailand. Currently, it has approximately 45,000 faculty members and students (MHESRI, 2018). In 2017, Chulalongkorn University ranked as the second-best green university in Thailand and 90th globally (Chulalongkorn University, 2018). Chulalongkorn University implemented a campus master plan concept of "Green Axis", which includes green landscape, water resources, and irrigation systems, to improve university's environments and ecosystems.

Thammasat University, established in 1934, has around 30,000 faculty members and students (MHESRI, 2018). Thammasat University consists of four campuses: Tha Pra Chan in the old town of Bangkok, Rangsit campus in Pathumthani, Pattaya in Chonburi Province, and Lampang Province. The Rangsit campus, which officially opened in 1986, was selected as a study area with a total area of 257.52 hectares (Thammasat University, 2019).

2.2. Data

2.2.1. Sentinel-2

GEE combines a multi-petabyte catalog of medium- to high-resolution satellite imagery and geospatial datasets with planetary-scale analysis capabilities, and it is available for scientists, researchers, and developers so that they can quantify the differences on the earth's surface. GEE includes satellite datasets, such as Sentinel-2, Landsat over 40 years, and several other satellite platforms, which are entirely free for research and academic purposes. We used GEE to access and process the Sentinel-2 10-meter resolution imagery for the urban tree cover mapping of 17 selected campuses in 2020. **Figure 2** illustrates the locations and tree covers of the campuses of Chulalongkorn University and Thammasat University Rangsit using Sentinel-2 data.

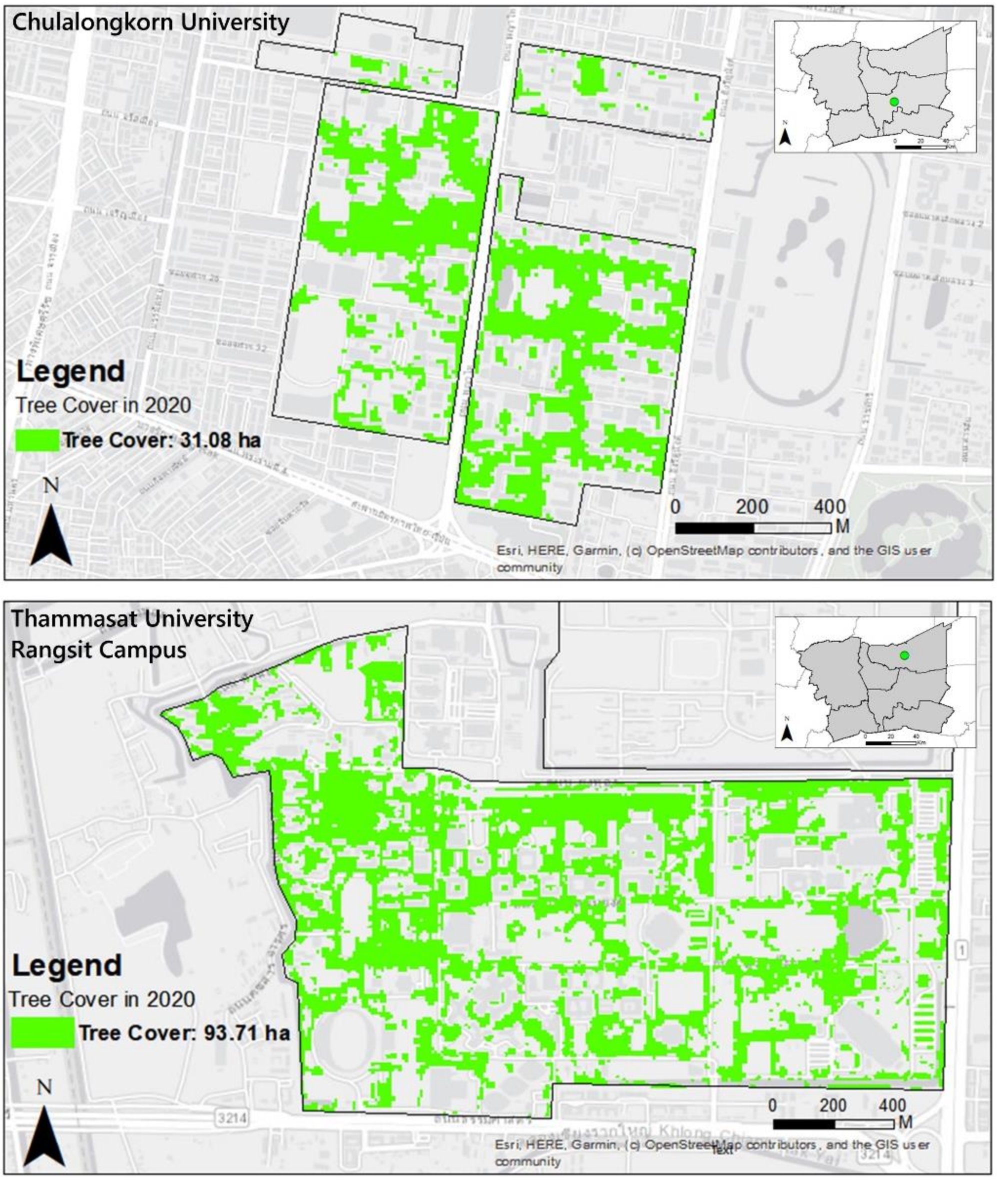


Figure 2. Locations and tree cover of the campuses of Chulalongkorn University and Thammasat University Rangsit. Source: Authors.

2.2.2. Aerial photos

DroneDeploy and the DJI technology are commonly used for aerial image capturing (using drones) and are intensively used in several applications, including forestry mapping, agriculture, and tree detection. In this study, we applied the drone Phantom 4 Pro to capture high-resolution imagery at 25 locations at Chulalongkorn University and three locations in the Thammasat University Rangsit Campus using DroneDeploy. The aerial photos were processed to an orthomosaic map. **Figure 3** shows flight planning examples using DroneDeploy at Chulalongkorn University and Thammasat University, respectively. To get the tree height, we used point-cloud data derived from the DroneDeploy software (**Figure 4**).

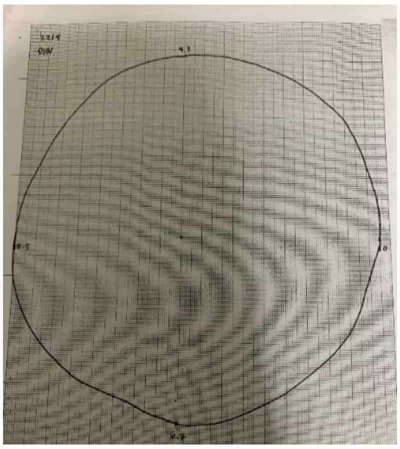
Figure 3. Flight planning and image capturing examples at Chulalongkorn University and Thammasat University Rangsit Campus. Source: Authors.

Figure 4. Example of tree point-cloud data at Chulalongkorn University. Source: Authors.

2.2.3. Tree inventory

The tree inventory data at Chulalongkorn University and Thammasat University Rangsit Campus are used for validation. The tree inventory of Chulalongkorn University, collected in 2016, consists of 4526 trees. The inventory provides the following six types of primary information about trees: general information, trunk, branches, leaves, roots, and other abnormalities. The inventory of the Faculty of Architecture and Planning at Thammasat University Rangsit Campus, collected in 2020, consists of 714 trees (Kaewkhow and Srivanit, 2021; Srivanit et al., 2021). In this study, the general information on trees was used to estimate carbon stock and sequestration. The information about a tree includes its ID, general name, scientific name, family, height in meters, diameter at breast height (DBH) in centimeters, canopy area in square meters, canopy density level, picture, and canopy sketch. **Table 2** shows an example of the information on a tree at Chulalongkorn University.

Table 2. Example of the information of a tree at Chulalongkorn University.

ID	**ART007**
General name	Raintree (จามจุรี)
Scientific name	Albizia saman
Family	FABACEAE
Height (m)	13
DBH (cm)	178
Canopy area (sq.m.)	308.3
Level of canopy density	Normal
Picture of tree	
Sketch of canopy	

2.3. Methodology

Figure 5 shows the methodological framework of this study. The remote sensing data from the Sentinel-2 imagery of the university campuses in the BMR and the drone data of the two case study campuses were used as the primary database. To validate the aerial imagery captured by drone, a tree inventory and field survey were conducted. Further details are provided in the following sections.

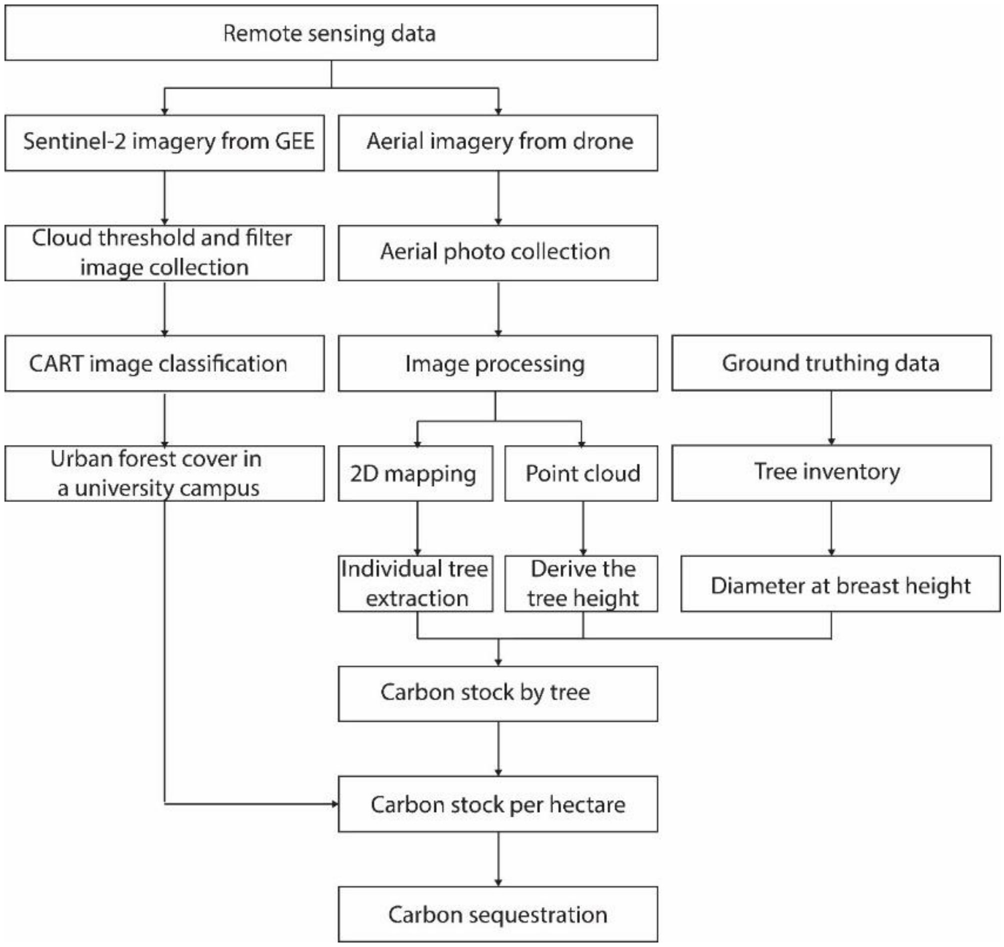


Figure 5. Research operational framework. Source: Authors.

2.3.1. Sentinel-2 satellite data

Available since 2013, the Sentinel-2 10-m resolution imagery helps in the accurate extraction of urban forest covers with the use of a GEE cloud computing platform for image collection. The GEE cloud computing classification and regression tree (CART) method was applied to map the urban forest cover areas in the selected universities in the BMR. The satellite imagery data used in this study is from January to August 2020. The training data consisted of 1045 points, which were divided into four classifications: tree cover (300 points), urban areas (461 points), water (93 points), and other vegetation (200 points). The results were validated against 3708 points in the same classifications: tree cover (2627 points), urban areas (420 points), water (240 points), and other vegetation (421 points). An overall accuracy is 83.92%. For the tree cover classification, the user accuracy is 97.12%, while the producer accuracy is 82.21%. The user accuracy of urban, water, and other vegetation is 68.30%, 78.65%, and 52.58%, respectively, while the corresponding producer accuracy is 88.73%, 93.79%, and 86.38%, respectively. The overall Kappa coefficient is 0.68, which is considered substantial.

The data from the urban forests on the campuses combined with the drone imagery data were used to estimate the carbon stocks and carbon sequestration of university trees on the basis of the Good Practice Guidelines of the Intergovernmental Panel on Climate Change (IPCC).

2.3.2. Aerial imagery from drone using UAV

The aerial images, high-resolution imagery, and point-cloud data from drones are essential for identifying individual trees and their heights and for estimating tree carbon stocks. We first selected the plots for flying the drone and then planned the flight to obtain an aerial photo collection. Afterward, we processed the collected images using DroneDeploy. To extract individual trees from the drone imagery, we employed the Agremo tool in the selected drone flying areas at Chulalongkorn University and Thammasat University Rangsit Campus. We then used two-dimensional maps and drone point-cloud data to extract the tree heights using the ArcGIS LiDAR Lastools datasets.

2.3.3. Carbon stock and sequestration assessment

The calculated tree heights were validated by crosschecking individual tree heights and DBH using the tree inventory data of Chulalongkorn University and Thammasat University. The tree density, height, and carbon stocks per hectare at different universities can vary, even within the same campus. Therefore, we selected the main quadrangle of Chulalongkorn University (14.6 hectares) and the whole area of the Faculty of Architecture and Planning of Thammasat University (2.91 hectares) as sites for the field survey (**Figure 6**). The tree inventory data combined with the field survey were used to validate the drone imagery and point-cloud results. The estimation process was as follows:

1) Validation of the drone-based tree detection, tree inventory, and survey.
2) Calculation of the above- and below-ground biomasses.
3) Assessment of the carbon stock, carbon stock per hectare, and average carbon stock per hectare.
4) Estimation of the carbon stocks of the selected universities in the BMR.
5) Estimation of the carbon sequestration of the urban university campuses in the BMR.

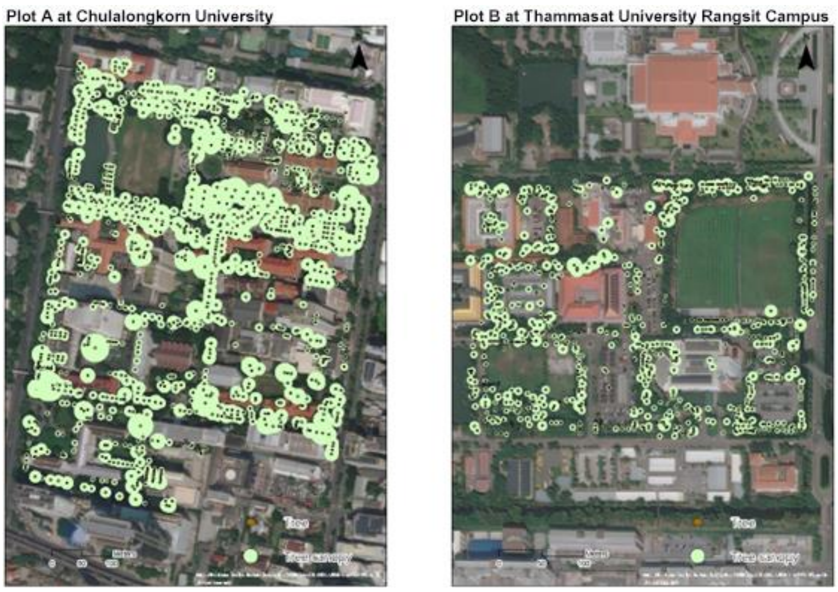


Figure 6. Selected plots for assessing the average carbon stocks per hectare. Plot A (left) at Chulalongkorn University and Plot B (right) at Thammasat University Rangsit Campus. Source: Authors.

In the calculation of the aboveground biomasses in this study, the types of trees are divided into evergreen and deciduous classifications. In plots A and B, there are 1,863 trees, representing 157 species. Specifically, in plot A, 22% of the trees are evergreen and 78% are deciduous, while in plot B, 24% of the trees are evergreen and 76% are deciduous.

The aboveground carbon stock estimation for evergreen is calculated using the allometric equations of Terakunpisut et al. (2007). The equations are as follows:

$$WEs = 0.0509 \times (D^2H)^{0.91}$$
$$WEb = 0.00893 \times (D^2H)^{0.977}$$
$$WEl = 0.0140 \times (D^2H)^{0.669}$$
$$AGBE = \mathrm{WEs} + \mathrm{WEb} + \mathrm{WEl}$$

where,

WEs is the mass of the evergreen tree stems/trunks (ton/ha),

WEb is the mass of the evergreen tree branches (ton/ha),

WEl is the mass of the evergreen tree leaves (ton/ha),

D is the diameter at breast height (cm),

H is the height of a tree (m),

and *AGB*E is the aboveground biomass of an evergreen tree (kg).

For deciduous trees, the aboveground carbon stock estimation is calculated using Ogawa et al.’s (1965) allometric equations. The parameters in the equations of deciduous trees differ from those of evergreen. The equations are as follows:

$$WDs = 0.0396 \times (D^2H)^{0.9326}$$
$$WDb = 0.003487 \times (D^2H)^{1.0270}$$
$$WDl = ((28.0/\mathrm{Ws}+\mathrm{Wb}) + 0.025)^{-1}$$
$$AGBD = \mathrm{WDs} + \mathrm{WDb} + \mathrm{WDl}$$

where,

Ws is the mass of the deciduous tree stems/trunks (ton/ha),

Wb is the mass of the deciduous tree branches (ton/ha),

WDl is the mass of the deciduous tree leaves (ton/ha),

and *AGBD* is the aboveground biomass of a deciduous tree (kg).

Therefore, the aboveground carbon stock estimation of trees is as follows:

$$Ws = WEs + WDs$$
$$Wb = WEb + WDb$$
$$Wl = WEl + WDl$$
$$AGB = AGBE + AGBD$$

where,

Ws is the mass of the tree stems/trunks (ton/ha),

Wb is the mass of the tree branches (ton/ha),

Wl is the mass of the tree leaves (ton/ha),

and *AGB* is the aboveground biomass of a tree (kg).

Several studies used the root: shoot biomass ratios proposed by Cairns et al. (1997) to estimate the below-ground biomass (BGB). In this study, BGB was approximately calculated as 0.24 of the AGB since the BMR is in the tropical latitudinal zone (Cairns et al., 1997).

The carbon stock can be estimated by converting the above- and under-ground biomasses to the total dry biomass at the average proportion of 47% (IPCC, 2006).

Then, carbon sequestration, the annual rate of carbon storage in the above- and below-ground biomasses, can be assessed (McPherson et al., 1994). The current average annual increments (CAIs) of the DBH and the height of the typical trees in Thailand are 0.62 and 0.53 centimeters, respectively (Poosaksai et al., 2018). In this study, the mean annual increment of the DBH of the trees in urban forests is 0.62 centimeters per year, and the mean annual increment of the height is 0.53 centimeters. We assumed the same growth rate for all woody vegetation because street trees in Bangkok generally do not vary much in terms of species (Thaiutsa et al., 2008; Kjelgren et al., 2011).

The tree biomass was calculated using allometric equations to validate the carbon stocks and carbon sequestration. The average carbon stocks per hectare from Chulalongkorn University and Thammasat University Rangsit Campus were then used to estimate the total carbon stocks in the other selected university campuses in the BMR. The results of carbon sequestration on campus are converted to carbon dioxide (CO_2) sequestered on campus by multiplying the weight of carbon by 3.6663, which is the ratio of CO_2 to carbon (De Villiers et al., 2014).

3. Results and discussion

Estimation of carbon stock and sequestration

After validating the data from the drone-based tree detection, tree inventory, and field surveys at Chulalongkorn University (one of the oldest universities in Thailand) and the Faculty of Architecture and Planning at Thammasat University's Rangsit Campus, the DBH information and height of trees are used for calculating biomass, carbon stock, and carbon sequestration, as shown in **Table 3**. At Chulalongkorn University, approximately 39.87 tons of carbon per hectare have been accumulated and stored in the urban forest on campus. The majority of the trees have been on the Chulalongkorn University campus for several decades, some with historical value. More than 4,500 trees on the campus are estimated to sequester 2.31 tons of carbon (or 8.48 tons of CO_2) per hectare per year. At Thammasat University, the carbon stock is approximately 39 tons of carbon per hectare. Most of the trees on the Thammasat University campus have also been there for several decades. The average carbon sequestration is estimated at 3.54 tons (or 12.97 tons of CO_2) per hectare per year. Based on the data from these two campuses, the carbon stock is calculated at the weighted average of 39.81 tons of carbon per hectare, while the weighted average of sequestration is estimated at 2.52 tons of carbon (or 9.22 tons of CO_2) per hectare per year. These two parameters are also used for other selected universities' carbon stock and sequestration calculations.

Table 3. Calculation of the biomass, carbon stock, and carbon sequestration in the study areas.

Campus	**Ws (ton/ha)**	**Wb (ton/ha)**	**Wl (ton/ha)**	**AGB (ton/ha)**	**BGB (ton/ha)**	**Carbon stock (ton/ha)**	**Carbon sequestration (ton/ha/yr)**	**CO_2 sequestration (ton/ha/yr)**
CU	52.59	13.71	1.03	67.32	17.50	39.87	2.31	8.48
TU	52.21	12.94	1.51	66.66	17.33	39.48	3.54	12.97
Weighted Average	52.53	13.58	1.11	67.22	17.48	39.81	2.52	9.22

Table 4 shows that the large campuses of Thammasat University and Mahidol University include extensive tree cover areas that can store more than 3300 tons and sequester more than 750 tons of CO_2 per year. Meanwhile, the Asian Institute of Technology, a medium-sized campus with a high ratio of tree-covered areas, can store approximately 3000 tons and sequester more than 680 tons of CO_2 per year. Conversely, medium-sized campuses with a medium ratio of tree-covered areas, such as Chulalongkorn University and Kasetsart University, have medium levels of carbon stock and carbon sequestration.

Table 4. Carbon stock and sequestration of the 17 selected universities in the BMR.

ID	University name	University area (ha)	Tree cover (ha)	The ratio of tree cover to campus area	Carbon stock (ton)	Carbon sequestration (ton/year)	CO_2 Sequestration (ton/year)
1	Asian Institute of Technology	99.89	73.81	0.74	2938.03	185.69	680.88
2	Bangkok University	62.73	23.89	0.38	951.12	60.11	220.42
3	Bangkokthonburi University	27.20	4.11	0.15	163.57	10.34	37.91
4	Chulalongkorn University	90.65	31.08	0.34	1237.20	78.20	286.72
5	Kasetsart University	140.62	44.83	0.32	1784.32	112.78	413.51
6	King Mongkut's University of Technology Thonburi	21.65	4.09	0.19	162.98	10.30	37.77
7	King Mongkut's Institute of Technology Ladkabang	99.15	30.74	0.31	1223.74	77.35	283.60
8	Mahidol University	170.76	83.62	0.49	3328.54	210.38	771.38
9	Nakhon Pathom Rajabhat University	36.03	15.15	0.42	603.20	38.12	139.79
10	Phranakhon Rajabhat University	26.31	7.34	0.28	292.12	18.46	67.70
11	Rajamangala University of Technology Krungthep	21.15	6.63	0.31	263.98	16.68	61.18
12	Rajamangala University of Technology Thanyaburi	18.53	7.17	0.39	285.37	18.04	66.13
13	Ramkhamhaeng University	48.97	8.60	0.18	342.45	21.64	79.36
14	Rangsit University	38.78	8.24	0.21	328.18	20.74	76.05
15	Silpakorn University	62.60	33.68	0.54	1340.60	84.73	310.68
16	Sukhothai Thammathirat University	22.18	5.34	0.24	212.50	13.43	49.25
17	Thammasat University	257.53	93.72	0.36	3730.48	235.78	864.53

4. Discussion

Initially, this study focused on measuring individual DBH and tree heights from Chulalongkorn University and Thammasat University's Rangsit Campus. Subsequently, the average carbon stock and sequestration are applied to other universities, relying on averages that may not precisely represent the tree species distribution. However, this estimation provides a reasonable basis for a campus forest comparison. This study also benefits further carbon sequestration research and future sustainability management.

Table 5. The proportion of carbon emissions and sequestration.

	Year	CO_2 emissions	Estimated CO_2 Sequestration	Percent
Chulalongkorn University	2018–2020	55,037	286.72	0.52%
Thammasat University	2010	34,355	864.53	2.52%
Kasetsart University	2017	66,855	413.51	0.62%
Mahidol University	2019	33,111	771.38	2.33%

Comparing the proportion of carbon sequestration and annual carbon emissions can present the status of the net-zero carbon campus. However, due to limited information on the GHG emissions of universities in Thailand, data from only three universities are available. The results from **Table 5** show that a small percentage, i.e., less than 1% of the total annual emissions or 55,307 tons of CO_2 emissions (Chulalongkorn University, 2020) can be sequestered at Chulalongkorn University. Moreover, Thammasat University produced 34,355 tons of CO_2 emissions in 2010 (Usubharatana and Phungrussami, 2014), Kasetsart University produced 66,855 tons of CO_2 emissions in 2017 (Kasetsart University, 2018), and Mahidol University emitted 33,111 tons of CO_2 emissions in 2019 (Phuynongpho, 2021). These hold higher proportions of sequestered CO_2, i.e., 0.5%–2.5% of the total emissions. These percentages are relatively similar to those of universities in other countries such as less than 1% at the University of California, Northridge (Cox, 2012), 2.4% at the SUNY Polytechnic Institute (Bremer et al., 2020), and 6% at KIWI University (De Villiers et al., 2014).

Although the proportion of carbon sequestration from an urban forest on campus to CO_2 emissions of a university might not be substantial, carbon sequestration with an urban forest on campus can play a significant role in raising awareness of green initiatives and sustainability, place-making, improving campus and urban environments, and providing urban ecological services. In addition to green campus initiatives, many universities are implementing policies toward carbon neutrality through waste management, energy conservation, pollution reduction, and tree planting.

Chulalongkorn University, for example, is committed to achieving Net Zero Greenhouse Gas Emissions by 2050 (Chulalongkorn University, 2023). To achieve this, the university is transitioning to renewable energy, especially solar power, enhancing energy efficiency, and promoting sustainable practices such as green building designs and waste reduction. The carbon sequestration of the trees helps in several ways, such as reducing greenhouse gases, improving the campus's ecological health, and contributing to a sustainable and biodiverse environment. The planting and maintenance of trees also increases the green cover and contribute to a lower carbon footprint. Integrating tree carbon sequestration into the university's research and educational initiatives contributes to the university's commitment to sustainability education and innovation. Through these contributions, the carbon sequestration of trees not only helps the university achieve its sustainability goals but also enhances its standing in global sustainability rankings.

5. Conclusion

The global awareness of GHG emissions has prompted many countries to commit to reducing their carbon emissions. The high concentration of anthropogenic activities in urban areas has led to large amounts of emissions. Thus, urban forests play a key role in sequestering atmospheric carbon and providing ecosystem services for urban populations, and the understanding of carbon stocks and carbon sequestration from existing tree inventories is essential for managing urban forests for carbon reduction. The urban forests in developing countries tend to decrease sharply. However, the urban campuses in such countries are usually covered by large trees, having the potential to serve as urban forests someday. These dovetail into the commitments of many universities to become more "green" and environmentally friendly. In Thailand, for example, some universities have joined the Green University Initiative and have implemented several campus improvements with a focus on the environment.

In this study, we aimed to assess the carbon sequestration of seventeen university campuses in the BMR using Sentinal-2 satellite data and drone aerial photos. Two campuses were selected for ground-truth validation by using their tree inventories: Chulalongkorn University and Thammasat University Rangsit Campus. The results have measured the per-unit contribution of tree cover areas to carbon stock and carbon sequestration. Assessing the stocks and sequestration of carbon can be an initial baseline for monitoring and managing urban forests to maintain or maximize the ability of stocking and sequestrating carbon. In addition, design guidelines for campus master plans can be applied to reduce carbon emissions.

Universities can establish policies to increase greenhouse gas (GHG) offsets by extrapolating future forest carbon from their current inventory. There are several strategies that can be applied to achieve this. For instance, the selection of tree species can help increase additional carbon stock. Similarly, better management and maintenance of existing forest areas on campus can lead to improved tree growth and maximum productivity yield. In cases where urban campuses have no available space, acquiring additional land and planting more trees outside of the main campus can be another bold step towards proposing a carbon sequestration plan.

In this analysis, we have identified several limitations. Due to the COVID-19 pandemic in Thailand, we were unable to travel to the survey fields, which restricted our ability to collect more details on tree inventories. To validate the ground truth, future studies can include more campuses. Moreover, it would be useful to investigate the carbon stock and sequestration ability of specific types of trees. For future analyses, we recommend incorporating other elements of campus master plans, such as building footprints, roads, and pedestrian networks.

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