Empirical Determination of the Carbon Impacts of Urban Forest Management in Hong Kong: Removal of *Acacia confusa* and *Leucaena leucocephala*

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Abstract. Urban trees contribute to decarbonisation. However, the removal of trees may release the stored carbon within them. In Hong Kong, *Acacia confusa* and *Leucaena leucocephala* are being removed, but with unknown carbon impacts. This industry-academia-government collaborative research aimed to: (1) report the amount of carbon stored inside *Acacia confusa* and *Leucaena leucocephala* harvested from slopes; (2) estimate the carbon storage of a tree using dendrometric measurements; and (3) explain the variation in carbon content percentage of urban trees with respect to tree species, part of the tree, and position within the part. 10 *Acacia confusa* and 10 *Leucaena leucocephala* were harvested during March–September, 2023. Each tree was weighed for carbon storage estimation. Results showed that *Acacia confusa* had higher mean wood volume, biomass and carbon storage than *Leucaena leucocephala*. The mean carbon content of the analysed samples (45.53−52.58%) were mostly significantly different from 50%. But the difference may become insignificant depending on how volatile carbon loss was controlled. Diameter at breast height (mm) was a significant predictor of carbon storage (kg) for both *Acacia. confusa* (β = 0.9574) and *Leucaena leucocephala* (β = 0.3909). Significant interaction between tree species and tree part on carbon content percentage was confirmed. This research demonstrated the impacts of past arboricultural decisions on present decarbonisation plans.

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1 Introduction

Carbon sequestration by trees may contribute to carbon neutrality goals set by municipal governments around the world. Biologically speaking, the potential photosynthetic rate of trees increases with ambient temperature and carbon dioxide concentration [1]. Urban areas contain various anthropogeneic carbon emissions sources and are warmer than the rural surroundings. Urban trees may sequester carbon more efficiently than their rural counterparts, alongside the many ecosystem services ushered by trees [2]. Therefore, trees can be described as carbon sinks inside urban areas.

Tree are important landscape elements of urban green space. Yet, tree removal are sometimes, if not often, necessary due to various reasons. Declining trees are removed for tree risk mitigation. Invasive species are also actively removed. After removal, decomposition will return part of the carbon sequestered by the lifetime of the removed trees back to the atmosphere [3]. Theoretically, the worst-case scenario is the complete loss of all tree-sequestered carbon to the atmosphere, when the carbon of decomposed organic matters fails to be transferred to the soil biota. Anyways, accurate figures about the carbon storage of trees are the prerequisites of understanding the carbon cycle and balance of urban tree removal operations.

In Hong Kong, since 1950's, >1,700,000 Acacia confusa was planted for slope stabilisation and soil re-nourishment purposes [4]. *A. confusa* can achieve 15 m in height. Unfortunately, *A. confusa* is a short-lived species. Senescent specimens are being removed. Yet, logs and foliage infected by pathogens are rejected by composting or wood recycling facilities. *Leucaena leucocephala* was planted in abandoned quarries in isolated spots for ecological rehabilitation. However, viable propagules can now be commonly found in Hong Kong. The carbon impacts arising from the removal of these two species.

Wood and foliage are carbon-based organic materials in which tree-borne carbon is stored. By examining the organic carbon content of wood and foliage samples of a tree, the carbon storage of the whole tree can be extrapolated. In many large-scale studies, carbon storage in a tree is estimated to be 50% of its biomass. But the tenacity of this assumption has been challenged [5, 6]. Accuracy in carbon content percentage can be enhanced by rigorous laboratory methods of the determination of carbon content. In particular, efforts can be spent on minimising the loss of volatile carbon [7]. Also, the variation in carbon percentage among tree tissues would deserve extra study since wood and foliage may not be chemically homogenous in different parts of a tree [8]. Furthermore, dendrometric variables may be useful in the prediction of carbon storage of a tree. Systematic investigation of carbon storage in trees has been carried out in Central America [6], North America [5, 9], Eastern Europe [7], and Eastern Asia [10]. This paper documents a preliminary exploration of carbon storage and carbon content percentage of urban trees.

The objectives of this study were to: (1) report the amount of carbon stored inside *A. confusa* and *L. leucocephala* harvested from slopes; (2) estimate the carbon storage of a tree using dendrometric measurements; and (3) explain the variation in carbon content percentage of urban trees with respect to tree species, part of the tree, and position within the part. In particular, whether 50% of a tree's biomass is carbon would be tested using t-tests. The explanatory power of dendrometric variables on a tree's carbon storage would be shown by correlation coefficients and regression models. Finally, the effects of tree species, part of the tree, and the position within the parts on the variation in the carbon content percentage would be explained using a mixed-effects model.

2 Methods

2.1 Study area

This collaborative study was conducted in the Kowloon Peninsula, Hong Kong (22°21'23"N, 114°8'11"E). According to the Köppen-Geiger climate classification, Hong Kong has a monsoon-influenced humid subtropical climate (Cwa) [11]. Approximately one-fourth of Hong Kong's land area is built-up area. Vegetated slopes made up a portion of the city's urban green space, which is actively maintained. Biodiversity enhancement and tree risk mitigation have caused the modification of the vegetation composition on urban slopes [12]. Large-scale urban tree removal has been initiated. But the implied carbon impacts are to be quantified.

A. confusa and *L. leucocephala* originated in the Philippines and the central American respectively. Hence, both are exotic in Hong Kong's ecological context. *A. confusa* features relatively short life span. Some individuals are causing tree risk conerns. *L. leucocephala* are common on slopes. In local decarbonisation plans, data of carbon impacts related to urban forest management are required. This research has been commissioned to probe into the carbon content percentage and storage of these two common urban tree species.

2.2 Tree samples collection

Tree samples were collected in collaboration with local arboricultural practitioners. Sampling work took place at the site of tree felling operations. From March, 2023 to September, 2023, a total of 20 trees were harvested, consisting of 10 *A. confusa* and 10 *L. leucocephala*. The diameter at breast height (mm), tree height (m), and crown radius (m) were measured before tree felling. Only the above-ground structure of each tree was harvested.

Since previous studies found significant carbon content variation among tree tissues, this study investigated such variation in detail. Each tree was first divided into three parts: (1) trunk; (2) branches; and (3) foliage. Trunk was defined as the single stem supporting the tree crown. In this preliminary research, only single-stemmed trees were collected by the principle of simplicity. Branches referred to first-order branches only. Foliage included the remaining above-ground parts, mainly twigs and leaves, which formed most of the tree crown.

For the trunk and the branches, every piece of cut logs was measured in terms of its diameter (mm), length (m) and fresh weight (kg). However, for foliage, bundles of twigs and leaves were tied together for weighing. Trunks and branches were cut into smaller pieces and transferred to the laboratory, together with some twigs and leaves. Samples that were transferred back to the laboratory were randomly selected.

2.3 Laboratory work

Wood samples were scrapped from the centre and the side of the cross-section of the cut logs of the trunks and branches, corresponding to the heartwood and the sapwood. Foliage samples, i.e. twigs and leaves, were cut into smaller pieces. Samples were measured for fresh weight (g), and oven-dried (65 °C) until constant weight, and re-weighed for moisture content (%). Dry samples were crushed and sieved to 0.2 mm. Finally, approximately 5.0 mg of the samples were sent to a total organic carbon analyser (PRIMACS, Skalar, Breda) to obtain the carbon content (%). To uphold representativeness, the laboratory work was triplicated.

Precautions were taken to minimise the loss of volatile carbon. First, instead of grinding, wood shavings were obtained through scrapping [13]. Cut logs of trunks and branches were scrapped, using a 13 mm-diameter drill bit and a hammer driver drill (DHP487Z, Makita, Anjo) running at its lowest speed. Second, all samples were oven-dried at 65 °C, which is a rather low temperature [14]. Third, instead of a grinding mill, a food blender was used in short bursts to powder the samples [15]. All these strategies minimised the exposure of the samples to heat and the loss of volatile carbon.

2.4 Data analysis

Simple linear regression models were constructed to generate allometry equations for estimating carbon content. In the model, diameter at breast height (mm), tree height (m), and crown width (m) served as predictor variables, whereas the above-ground carbon storage (kg) of the trees was the outcome variable. Carbon storage was estimated by multiplying the carbon content percentage to the biomass of different tree parts. Since biomass excludes water, the above-ground biomass of each tree was solved by:

$$M = W_{trunk}(1 - MC_{trunk}) + W_{branch}(1 - MC_{branch}) + W_{foliage}(1 - MC_{foliage}) \quad (1)$$

M referred to the above-ground biomass (kg) of a tree, *W* was the sum of fresh weight of each part of the tree, namely *trunk*, *branch*, and *foliage*, and *MC* was the empirically measured mean moisture content (%) of the samples obtained from the respective part.

Finally, a mixed-effects model was constructed to understand the observed variation in carbon content percentage. Tree species (*A. confusa* and *L. leucocephala*), and tree part (trunk, branch, and foliage) were fixed factors. Their two-way interaction term was also included. As the vegetative samples were randomly selected, the position where samples were taken, position (centre, side, leaf, and twig) thus served as a random factor. In this study, all data analyses were conducted in *RStudio* [16]. Data visualisation was aided by package *ggplot2* [17]. The mixed-effect model analysis was achieved using package *lmerTest* [18].

3 Results and discussion

3.1 Dendrometric dimensions and carbon storage

In this research, 10 *A. confusa* and 10 *L. leucocephala* were collected. *A. confusa* were generally larger than *L. leucophala* in terms of diameter at breast height (229.4 mm vs. 129.7 mm), on average (Table 1). But, the relative difference (7.2 m vs 6.0 m) in tree height was smaller. Both species had comparable crown radius, with a mean difference of 0.1 m, which was marginal and difficult to measure in-situ. During field data collection, leaning trunk and crown asymmetry were observed. These reflected the high variability in tree form, which was shown in the dendrometric measurements.

The morphology of trees growing on slopes could be affected by habitat-specific environmental and ecological conditions [19, 20]. Slope inclination, site aspect, tree crown competition, soil fertility and many different factors could modify the architecture of individual trees. Also, crown clearing, crown base raising, dead branch removal and other tasks were regular management tasks related to slope trees [12]. Thus, on top of the environmental factors, artificial arboricultural operations exerted additional influences on the values of the dendrometric variables.

Table 1. Descriptive statistics of the two tree species, namely (a) *Acacia confusa* (n = 10) and (b) *Leucaena leucocephala* (n = 10) collected for this study. The mean value of their diameter at breast height (DBH) (mm), tree height (m), crown radius (m), wood volume of trunk and branches (m^3), biomass (kg), and estimated carbon storage (kg) is shown, and accompanied by the standard error in brackets.

		DBH (mm)	Tree height (m)	Crown radius (m)	Wood volume (m^3)	Biomass (kg)	Carbon storage (kg)
(a)	*Acacia confusa*	229.4 (36.2)	7.2 (0.8)	3.8 (0.5)	4.4 (1.2)	336.7 (85.8)	160.0 (40.9)
(b)	*Leucaena leucocephala*	129.7 (25.6)	6.0 (0.3)	3.7 (0.4)	0.9 (0.3)	61.0 (23.6)	27.7 (10.4)

However, the total wood volume of a tree may be a better indicator of its size. Similar to DBH, *A. confusa* had greater mean wood volume (4.4 m^3) than *L. leucophala* (0.9 m^3) (Table 1). Also, in terms of biomass, *A. confusa* had greater mean biomass (336.7 kg) than *L. leucophala* (61.0 kg). Carbon storage depended on biomass. Comparably, the respective mean carbon storage at 160.0 kg and 27.7 kg. The volumetric and massive variables showed a higher consistency in the relative difference between *A. confusa* and *L. leucophala*.

Carbon storage by trees can be expressed in an areal basis (kg/hectare). Although this research featured no landscape-scale surveying, numerical findings from past research were compared. American and European research found urban forest carbon stock estimates from 11,000 kg/hectare [21] to 25,100 kg/hectare [22]. Based on the carbon storage per single tree found in this research, such range corresponded to 69–157 *A. confusa* or 397–906 *L. leucoephala* per hectare. From the field observation during tree harvesting, such tree densities were exceeded.

When a tree has to be removed, its carbon storage could be quantified. Yet, weighing a tree in the field setting is impractical. A more feasible option is to correlate dendrometric variables with volumetric or massive variables. In fact, significant correlation coefficients were returned by correlating DBH with wood volume (r = 0.87), biomass (r = 0.86), and carbon storage (r = 0.85). Regression models also confirmed the significance of DBH (mm) as a predictor of carbon content (kg) for *A. confusa* (β = 0.9574) and *L. leucophala* (β = 0.3909), whereas tree height and crown radius were insignificant predicors. Considering the preliminary nature of this research, sampling efforts will still be needed to generate more data for a more representative carbon storage estimation based on dendrometric measurements.

3.2 Variation in carbon content percentage

In this research, the variation in the carbon content percentage was investigated. The mean carbon content percentage of different positions in different parts of the trees ranged from 45.53% to 52.58%. Most mean values were lower than 50%. Except for the twigs of *A. confusa*, one-sample t-tests showed significant difference from 50% ($p < 0.05$) for different positions of the different tree parts. The standard errors showed that the laboratory methods produced consistent results.

Table 2. Mean values of carbon content percentage (%) of the centre and side of the trunks and branches, and the leaves and twigs of the foliage collected from the (a) *Acacia confusa* and (b) *Leucaena leucocephala* samples, with the standard error in brackets.

		Trunk		Branch		Foliage	
		Centre	Side	Centre	Side	Leaves	Twigs
(a)	*Acacia confusa*	47.24 (0.50)	47.84 (0.69)	48.29 (0.48)	47.56 (0.48)	52.58 (0.45)	49.72 (0.45)
(b)	*Leucaena leucocephala*	46.66 (0.65)	46.69 (0.61)	46.23 (1.17)	47.34 (0.64)	46.98 (0.69)	45.53 (0.66)

During testing, despite the efforts to minimise the volatile carbon loss, some loss might still occur. Freeze-drying method was not used due to the unavailability of the equipment [13]. Past studies found a range of volatile carbon percentage from 1.20% to 3.00% [6, 7, 9]. In fact, additional t-tests were attempted by testing the observed carbon percentages (Table 2) plus 2.48%, which was the volatile portion in tropical hardwood [6], against the widely assumed 50%. Except the twigs of both species, no significant differences ($p > 0.05$) from 50% was found, if 2.48% was added. Therefore, whether 50% of a tree's biomass could be safely assumed to be carbon would depend on the part of the tree, and the percentage of carbon being volatile. Future local research is still required to quantify the influence of volatile loss on carbon content measurement within Hong Kong's context.

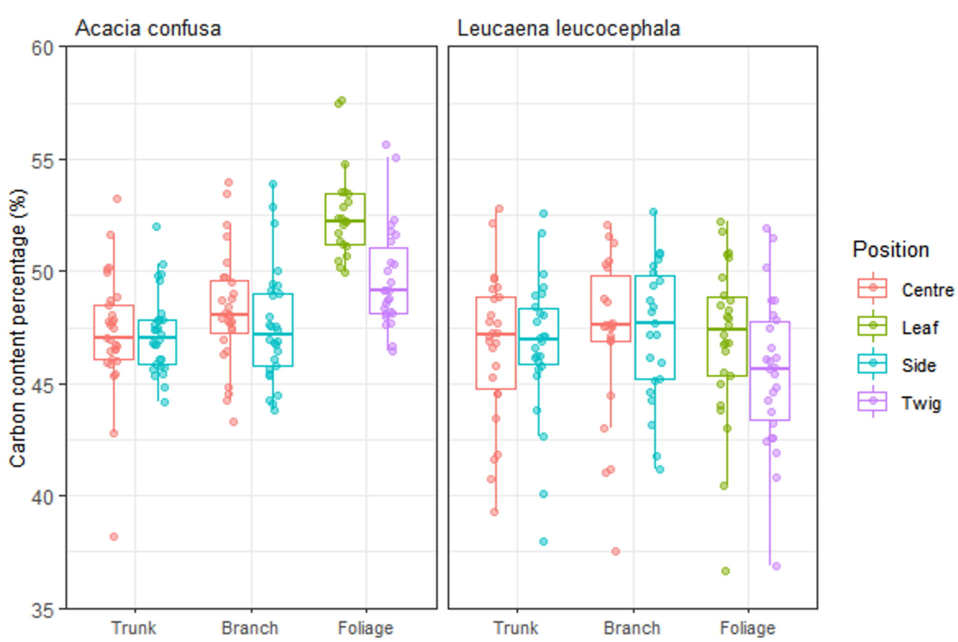

Fig. 1. Distribution of carbon content percentage (%) of *Acacia confusa* and *Leucaena leucocephala*. Vegetative samples were obtained from the centre and side of the cut logs of trunks and branches, as well as the twigs and leaves of the foliage.

Using a mixed-effects model, significant main and interaction effects in the variation of carbon content percentage were found. Different parts of the tree, as a main effect, yielded significant different carbon content percentage (Fig. 1). The significance was attributed to the higher carbon percentage of the foliage than the trunk and the branches, by 1.93–5.14% and 3.11–3.19%, respectively. Yet, tree species caused no significant main effects.

There was significant interaction between tree species and part of the tree. It was because *A. confusa* foliage had higher carbon percentages than the trunk and branches, whereas *L. leucocephala* foliage showed the opposite differences (Fig. 1). For instance, *A. confusa* foliage contained 3.54% more carbon than the trunk, whereas *L. leucocephala* foliage had 3.09% less, on average. As shown in Table 2, the relatively high carbon percentage of *A. confusa* leaves and the relatively low value of *L. leucocephala* could contribute to the significant interaction effect.

In past research, different tree tissues had different carbon content percentages. For instance, samples collected from Latvian softwood forests showed 1.1–2.5% difference between the trunk and the branches [7]. In Canadian boreal forests, 5.7% difference between tree bark and trunk was registered [9]. When comparing against these past findings, the current research found relatively smaller difference in woody tissues between trunk and branches samples, 0.28–1.05%. Yet, this research showed significantly higher carbon percentage in foliage samples.

The position where samples were obtained was randomly chosen. Thus, position was regarded as a random effect nested within the part of the trees. Such random effect was 0.73%. However, the residual stood at 3.26%, implying a rather substantial unexplained variation in carbon percentage. Such residual value may indicate the variation from tree to tree. Another parameter expressing the uncertainties in carbon content estimation is the margin of error. Past studies showed margin of error from 0.20% to 1.85% [5, 10]. In this research, intermediate values of margin of error were found among different parts of *A. confusa* (0.88–1.36%), but larger values in the case of *L. leucocephala* (1.20–2.30%).

4 Conclusion

A collaborative research was conducted in Hong Kong to report the amount of carbon stored inside *A. confusa* and *L. leucocephala* harvested from slopes, estimate the carbon storage of a tree using dendrometric measurements, and explain the variation in carbon content percentage of urban trees with respect to tree species, part of the tree, and position within the part. 10 *A. confusa* and 10 *L. leucocephala* were harvested for empirical dendrometric, massive, moisture and carbon content measurements. The complexities related to the estimation of carbon stock and the variation in carbon content percentage among tree tissues have been elaborated with the support of rigourous statistical analyses. Due to arboricultural decisions made in the past, tree removal programmes have to be implemented, partially offsetting some of the carbon sequestration benefits brought by these trees. In order to uphold sustainability in urban forest management, the long-term impacts of the operations made in the present moment must be carefully considered.

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References

1. E.D. Schulze, E. Beck, K. Müller-Hohenstein. *Plant ecology* (Springer Science & Business Media, Berlin, 2005)

2. L.F. Weissert, J.A. Salmond, L. Schwendenmann. Urban Ecosys, **20**, 663–674. (2017)
3. M.W. Strohbach, E. Arnold, D. Haase. Landsc. Urban Plan, **104**, 220–229. (2012)
4. Y.S.G. Chan, M.H. Wong, B.A. Whitton. Wat. Air and Soil Poll, **111**, 29–40. (1999)
5. S.H. Lamlom, R.A. Savidge. Biomass Bioenerg, **25**, 381–388. (2003)
6. A.R. Martin, S.C. Thomas. PloS One, **6**, e23533. (2011)
7. A. Bārdule, J. Liepiņš, K. Liepiņš, J. Stola, A. Butlers, A. Lazdiņš. Forests, **12**, 1292. (2021)
8. D.A. Jones, K.L. O'hara. Forestry, **85**, 99–110. (2012)
9. B. Gao, A.R. Taylor, H.Y. Chen, J. Wang. For. Ecol. Manag, **375**, 191–199. (2016)
10. S.C. Thomas, G. Malczewski. J. Environ. Manage, **85**, 659–662. (2007)
11. M.C. Peel, B.L. Finlayson, T.A. McMahon. Hydrol. Earth Syst. Sci, **11**, 1633–1644. (2007)
12. L.S.H. Lee, H. Zhang, K.T.K. Ng, S.C. Lo, A.S.L. Yu. J. For. Res, **34**, 1347–1358. (2023)
13. D.A. Jones, K.L. O'Hara. Tree Physiol, **36**, 1177–1189. (2016)
14. T.C. Silva, E.C.G. Araujo, C.R. Sanquetta, J.B.M. Coelho, E.B. Neto, L.P. Barreto. Rev. em Agronegocio Meio Ambiente, **14**, e8400. (2021)
15. S.E. Allen, H.M. Grimshaw, A.P. Rowland. *Chemical analysis*, in: P.D. Moore, S.B. Chapman, (Eds), Methods in Plant Ecology (Blackwell Scientific Publication, Oxford, 1986)
16. RStudio Team. *RStudio: Integrated Development for R* http://www.rstudio.com (RStudio, Boston, MA, 2020)
17. H. Wickham. *ggplot2: Elegant Graphics for Data Analysis* (Springer-Verlag, New York, 2016)
18. A. Kuznetsova, P.B. Brockhoff, R.H.B. Christensen. J. Stat. Softw, **82**, 26 (2017)
19. S. Getzin, K. Wiegand. For. Ecol. Manag, **242**, 165–174. (2007)
20. A.C. Lang, W. Härdtle, H, Bruelheide, C. Geißler, K. Nadrowski, A. Schuldt, M. Yu, G. von Oheimb. For. Ecol. Manag, **260**, 1708–1715. (2010)
21. M.W. Strohbach, D. Haase. Urban Plan, **104**, 95–104. (2012)
22. D.J. Nowak, D.E. Crane. Environ. Pollut, **116**, 381–389. (2002)