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Measure what you manage? Comparing urban forest composition metrics used in research assessing carbon and avian outcomes of urban forest management

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Abstract

Urban forests are multifunctional social-ecological systems that can contribute to both climate change mitigation and biodiversity conservation. However, management of urban forests for these objectives are often studied independently. Knowing which measures can be used to assess multiple objectives could enable integrated monitoring efforts and subsequently increase potentials for synergies in management. We compared the use of forest composition metrics in studies focused on carbon storage ($n = 109$) and avian diversity ($n = 158$) extracted from a published systematic literature map. Through qualitative content analysis, we developed a standardized set of 24 urban forest composition metrics spanning size, taxonomy, structure, tree characteristics, and presence of vegetation layer types. Analysis assessed frequency and co-occurrence of metrics for research assessing carbon or avian outcomes. Carbon-focused studies were dominated by a smaller and more restricted set of variables, with tree species composition and diameter measured in over 90% of studies. In contrast, avian studies used a broader and specialized suite of metrics, emphasizing different types of vegetation layers and diverse habitat features such as shrubs, cavities, and fruit resources. Co-occurrence analysis revealed tightly clustered measurement frameworks in carbon studies and somewhat more diffuse patterns in avian research. These results highlight how the same measures of urban forest composition have been and can be used to assess both avian and carbon management outcomes. Overlaps and gaps identified places where alignment in urban forest monitoring could improve the capacity to manage for multiple outcomes.

1. Introduction

Urban forests are multifunctional social-ecological systems (Escobedo *et al* 2019, Vogt 2024), encompassing the trees and associated vegetation in and around urban areas, cared for by diverse actors across the continuum ranging from downtown cores to suburban neighborhoods to peri-urban towns (Pickett *et al* 2026). Urban forests provide diverse benefits from shading sidewalks to intercepting stormwater to providing wildlife habitat, and can also be influenced through planning and management to further multiple positive conservation outcomes (Hale *et al* 2015, Sousa-Silva *et al* 2021, Bassett *et al* 2024). Despite the multifunctional potential of urban forests, managing ecosystems for multiple objectives in ways which increase synergies and avoid tradeoffs is a core challenge in ecology and ecosystem management at large (Nelson *et al* 2009, Bradford and D'Amato 2012, Turkelboom *et al* 2018). As urban forests

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are increasingly expected to act as nature-based solutions for human well-being and biodiversity conservation, understanding how management affects multiple outcomes has become increasingly important to maximize limited resources and avoid trade-offs.

Two critical, yet potentially conflicting, management objectives for urban forests are increasing carbon storage and sequestration (to mitigate climate change) and supporting wildlife populations (to mitigate the biodiversity crisis). Most empirical research in these areas understandably focuses on single outcomes (Campbell 2009, Ferenc *et al* 2014, Yang *et al* 2015, Mngadi *et al* 2022, Drolen *et al* 2023), yet managers must always contend with managing for many objectives. Analysis of forest composition provides a lens through which to understand variables that could be influenced through active management, such as the species and size of trees. Measures of forest composition—those that consider the distribution of tree and shrub species, age, size, or structure (Hutt-Taylor *et al* 2024)—have been shown to support varying outcomes for carbon or wildlife objectives. For example, (Lerman *et al* 2014) constructed habitat suitability indexes for nine bird species based on urban forest structural variables such as tree density and canopy cover. Similarly, (Millward and Sabir 2011), quantified the value of carbon dioxide offset and sequestration by urban trees using urban forest composition variables such as tree species, diameter at breast height (DBH), and height. However, the specific metrics by which composition is assessed differ broadly across studies. If the adage 'you manage what you measure' is true, understanding the differences in how urban forest composition is assessed is an important step towards successfully managing urban forests for multiple objectives, such as carbon-based climate change mitigation and biodiversity conservation.

Despite broad evidence linking various aspects of urban forest composition with specific conservation outcomes (such as carbon or wildlife), most research on outcome-based land and urban forest management has still been typically separated by disciplinary boundaries. A systematic literature map assessing the literature on urban forest management for carbon storage/sequestration and avian diversity (respectively) (Hutt-Taylor *et al* 2024), identified a significant number of articles from both bodies of literature investigating forest composition metrics, without any articles overlapping across both groups (Carbon, $n = 120$, Avian, $n = 160$). This disciplinary separation from wildlife biology is also evident in urban forestry professional training; urban foresters typically have limited wildlife experience in their training (Barron *et al* 2025), despite the strong interdisciplinarity of the field and often strong desire on behalf of professionals to support wildlife (Martin and Almas 2022). Understanding how to integrate monitoring efforts and synergistic management actions for multiple outcomes would help bridge this gap and make the best use of limited financial and logistical capacities of managers.

Here, we investigate the similarities and differences in how research approaches the role of urban forest composition as related to climate mitigation (carbon storage) and biodiversity conservation (avian diversity). Using an existing database from a systematic literature map of research on urban forest management for carbon-based climate change mitigation and avian diversity outcomes (Hutt-Taylor *et al* 2024), we ask how metrics of forest composition, specifically, are used differently in these bodies of literature. Our objectives include: (1) assessing the categories of forest composition metrics used in both bodies of literature (carbon vs. avian outcomes), (2) quantifying the frequency of use of each metric and level of co-occurrence or disconnection for composition metrics in the two research fields, and (3) identifying composition metrics and areas of research best suited to identify synergies or tradeoffs in managing urban forests for carbon and avian diversity outcomes.

2. Methods

2.1. Dataset

We assessed 271 articles extracted from a systematic literature map (Hutt-Taylor *et al* 2024). From this literature database of peer-reviewed, urban forest research articles from temperate climate zones, we retrieved articles using forest composition metrics (defined as 'considers the composition of tree and shrub species, age or size or structure') that investigated one of two groups: (1) carbon-based climate change mitigation outcomes ($n = 111$) or (2) avian conservation outcomes ($n = 160$). Overall, we first used a qualitative content analysis to identify the primary forest composition metrics employed in each study and subsequently analyzed and visualized these coded data to illustrate patterns across the literature. In the qualitative content analysis approach, we first developed a list of codes representing the primary metrics being used to assess forest composition (table 1). To create this list, author Corinne G Bassett (CGB) first employed a phase of primarily inductive coding (or 'open coding'), followed by a second phase of deductive coding (Tracy 2019). In the first phase, CGB created an initial list of forest composition metrics through open coding of summaries of forest measurement used in each study

Table 1. List of forest composition metrics extracted from carbon ($n = 109$) and avian ($n = 158$) urban forest research articles in a systematic literature map (Hutt-Taylor *et al* 2024). Metrics organized by category and including details used to make coding decisions.

Category	Forest composition metric	Details
Size	Total height	Estimate or measurement of total tree or shrub height, exact or in classes
	Crown height	Height from base of crown to top of crown, or crown base height if also measured total height
	Crown width/area	Horizontal measurement of crown size, in one or multiple directions
	Merchantable height	Bole height, height of portion of trunk that could be sold for usable lumber
	Diameter	Diameter measured as at a consistent height (i.e. DBH/DSH, diameter at base)
Species	Tree species composition	Using species or genus as variable of comparison
	Shrub species composition	Using species or genus as variable of comparison
Structure	Stem density	Stems or individuals/area, and basal area per area (not included when it was just a count of individuals)
	Planting arrangement	Compares spatial arrangement of stems or site design of planted stems (ex: how close stems are, what pattern they are in, etc) (does not include spatial arrangement with respect to other features e.g. Distance to buildings)
	Vertical layer assessment	Assessment of numbers of vegetation layers, structural complexity, etc (must estimate or describe something about the layers)
	Overall canopy cover[a]	Canopy cover from all vegetation layers (not just highest trees)
Tree characteristics	Plant functional types	Species groupings by traits or functions e.g. Deciduous/evergreen, conifer/broadleaf
	Tree condition	Assessment of tree health, including qualitative scales (e.g. Poor, fair, good) and quantitative estimates (e.g. Percent of crown with dieback, percent herbivory)
	Standing dead trees	Presence of or count of standing dead trees (also called snags)
	Perch/nest height	Height to potential perch or nest
	Cavity metrics	Any metric used to assess a tree cavity including presence of cavity, size, shape, etc.
	Fruit metrics	Any assessment of fruits including fruit density
	Age	Includes age estimates, age classes, and age of a forest stand, etc.
Vegetation layer type[b]	Tree layer[a]	Includes assessing presence of (Y/N) or extent of (% or area) cover that is trees
	Shrub layer	Includes assessing presence of (Y/N) or extent of cover that is shrub or understory
	Ground layer	Includes assessing presence of (Y/N) or extent of cover that is ground cover
	Vine layer	Includes assessing presence of (Y/N) or extent of cover that is vines
	Leaf litter layer	Includes assessing presence of (Y/N) or extent of cover that is leaf litter
	Coarse woody debris layer	Includes assessing presence of (Y/N) or extent of cover that is coarse woody debris

[a] We differentiated 'overall canopy cover' from 'tree layer,' with the former referring to assessments of overall cover from all vegetation (e.g. from aerial assessments), and the latter referring specifically to the presence or cover of trees.
[b] Metrics under 'vegetation layer type' referred to whether an article assessed presence of (Y/N) or extent of a certain layer of cover.

from the (Hutt-Taylor *et al* 2024) database, using 30% of each of group of literature (i.e. carbon and avian). As this list was created, CGB adjusted the phrasing of metrics iteratively (e.g. grouping 'DBH' and 'DSH' as 'diameter'). In the second phase, CGB reviewed and tested the list on summaries of a different 30% of each group and adjusted the metric list as needed. CGB tested the final list of metrics on the full texts of five papers from each group (carbon and avian) to ensure comprehensiveness and that each metric on the list was distinct (table 1). CGB and JL also grouped the final list into several categories based on the authors' experience and judgement, to aid in differentiating the 26 different metrics

Table 2. Definitions of carbon and avian success outcomes considered, as coded in database from Hutt-Taylor *et al* (2024).

Outcome	Outcome metric	Definition
Carbon	Aboveground biomass	Carbon measured by calculations considering aboveground forest components (allometric equations, etc)
	Belowground biomass	Carbon measured by calculations of forest components belowground (roots, shoots etc)
	Soil	Carbon stored in urban forest soil
	Infrastructure	Carbon stored within infrastructure (buildings, benches, materials)
	Dead wood/organic matter	Carbon stored in dead wood and organic matter within the urban forest (logs, leaf litter etc)
Avian	Behavior	Foraging behavior, oral communication (e.g. birds' ability to communicate through song), and/or migration (e.g. migration patterns, distances, and success)
	Breeding	Breeding success as affected by macro, meso, and micro landscape and habitat variables (e.g. parasitism, predation, nest abandonment, nest structure, and/or flight initiation distance FID)
	Biodiversity	Metrics of avian diversity (e.g. genetic, species, functional)
	Demographics/Patterns	Estimates of population changes (e.g. trends in population metrics), community changes (e.g. trends in community metrics), and/or species distribution (e.g. models the estimated distribution of species across a landscape).
	Resources	Intra-specific competition and/or inter-specific competition
	Survival	Individual survival/mortality (rate of mortality within a population or community) and/or nesting survival (rate of survival of eggs and nestlings within a population or community)

being assessed. Authors CGB and JL relied on the definitions of each term used within each article to make coding decisions.

We also used the database variables of carbon outcomes (i.e. above-ground biomass, below-ground biomass, dead wood/organic matter, infrastructure (timber buildings), soil) and avian success (i.e. behavior, biodiversity, breeding, demographic/patterns, resources, survival) (Hutt-Taylor *et al* 2024) and compared these outcomes with urban forest composition metrics extracted as a result of this new analysis (see table 2 for definitions of outcomes per Hutt-Taylor *et al* 2024).

Authors CGB and JL conducted data extraction through deductive coding of article full-texts using the final list of forest composition metrics (table 1). We assessed each metric from the list with the following inclusion criteria: 'Does this article measure this metric and explicitly use it to assess or compare carbon or avian outcomes?' (if yes, include). Metrics were included no matter the method of measurement e.g. tree diameter assessed manually with measurement tapes or remote sensing analysis; area-based measurements like tree cover from remote sensing or field-based estimates. When conducting full-text review, we read the title, abstract, then focused on methods and results sections. We conducted two calibration rounds, with CGB and JL independently assessing two avian and two carbon articles each, then meeting to discuss discrepancies, followed by assessing another four avian and four carbon articles each, and meeting again. After the second round, CGB and JL reached an average of 90% agreement (out of 25 potential codes for each article, there was an average discrepancy of 2.25 codes assigned) and discrepancies were easily resolved (Roach 2017). We continued data extraction independently, communicating frequently to discuss edge cases.

We found that two articles from the avian group (1% of original 160 articles) and two from the carbon group (1.8% of original 111 articles) did not measure any of the specific forest composition metrics defined in table 1 and were marked as N A and excluded from the final dataset used in analysis. The final dataset included avian, $n = 158$, and carbon, $n = 109$. We managed the database in a shared spreadsheet during data extraction.

2.2. Analysis

We conducted all data visualization and analyses in R (v4.5.2) using RStudio (Posit Team 2024). Code is available at:https://github.com/zule-lab/UFCompMetrics-Carbon-Avian (Bassett 2026) . We completed descriptive statistics and figures using the *ggplot2* package in R (Wickham *et al* 2026). We conducted analysis for sections 3.1 and 3.2 prior to 5 March 2026, the date of release of Posit Assistant in RStudio. The proportion-normalized frequency tables, co-occurrence analysis, and heatmap with dendrogram

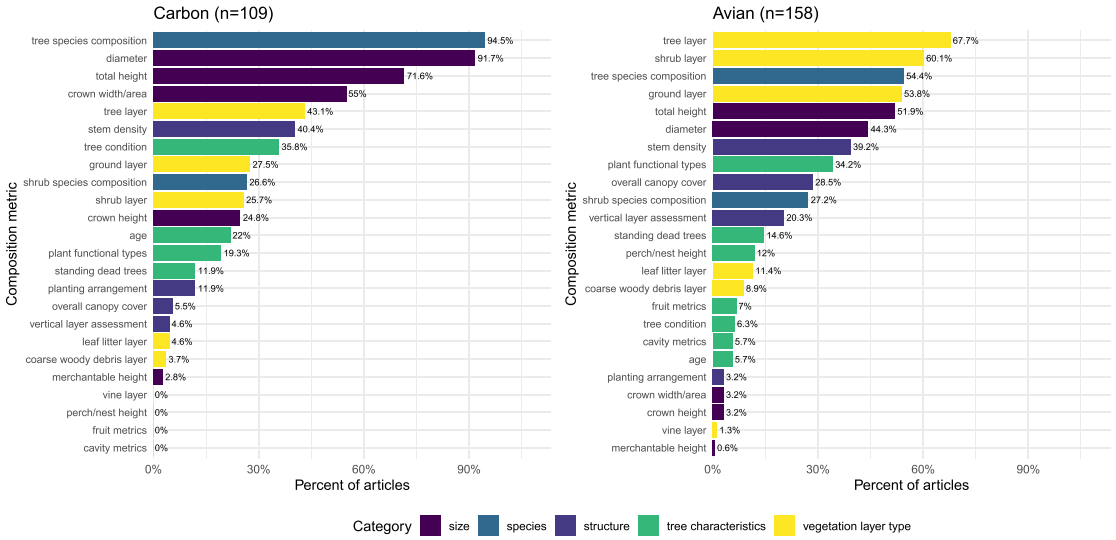


Figure 1. Percentage of articles that measured and explicitly used each forest composition metric to assess either carbon ($n = 109$) or avian ($n = 158$) extracted from urban forest research articles in a systematic literature map (Hutt-Taylor *et al* 2024). Colour represents the category of forest composition metric.

visualizations were generated using code written with assistance from Posit Assistant. The authors made all analytical decisions, interpretations, and reviewed all code.

To understand which metrics tended to be more commonly used together within a study we assessed co-occurrence among metrics for each group (avian and carbon) separately. First, we constructed separate binary article-by-metric matrices for the avian and carbon groups, with each matrix encoding the presence (1) or absence (0) of each metric within each article. Then, we measured pairwise co-occurrence using the Jaccard similarity index (Legendre and Legendre 2012), defined as the number of articles in which two metrics co-occur divided by the number in which at least one of the two metrics appears. We converted the resulting similarity matrices to Euclidean-compliant Jaccard distances (Gower and Legendre 1986) and clustered using hierarchical agglomerative clustering with the Ward. D2 linkage (Murtagh and Legendre 2014). Finally, we generated heatmaps with dendrograms to visualize similarity structure among metrics. We used packages *dplyr* (Wickham *et al* 2026), *tibble* (Müller and Wickham 2026), *tidyr* (Wickham and Girlich 2025), and *stringr* (Wickham 2025) in data processing and analysis, and *ggplot2* (Corbett *et al* 2026), *viridis* (Garnier 2018), *scales* (Wickham and Seidel 2025), and *pheatmap* (Kolde 2025) in creation of figures.

3. Results

3.1. Most frequent urban forest composition metrics for articles studying avian and carbon outcomes

Broadly, we identified that there were specific forest composition metrics used commonly in the carbon literature, whereas none of the forest composition metrics were used as extensively in the avian literature (figure 1). For example, the top two forest composition metrics in carbon literature (tree composition and diameter) were almost ubiquitous in their use as both were found in >90% of articles considered (figure 1). In comparison, none of the forest composition metrics identified in the avian literature were as commonly present in all studies, with the top metric (tree layer) appearing roughly in two-thirds of all articles considered (figure 1). Tree species composition was the only shared metric between the avian and carbon papers in the top three most common metrics. While this metric was found in almost all carbon articles (94.5%), conversely tree species composition was found in just over half of avian articles (54.4%). We extracted all 24 forest composition metrics (table 1) at least once from avian articles, while we found only 20 metrics present in carbon articles. The four metrics absent in carbon studies (but present in avian articles) were fruit metrics ($n = 11$ in avian articles), perch/nest height ($n = 19$), cavity metrics ($n = 9$), and vine layer ($n = 2$). We found no substantial differences in the number of individual metrics typically considered by papers studying avian (median = 5) and carbon outcomes (median = 6) of urban forestry (Supplementary Material figure S1).

We also found differences within the categories of forest composition metrics included in avian and carbon outcome studies (Supplementary Material figure S2). Within the size category of metrics, carbon

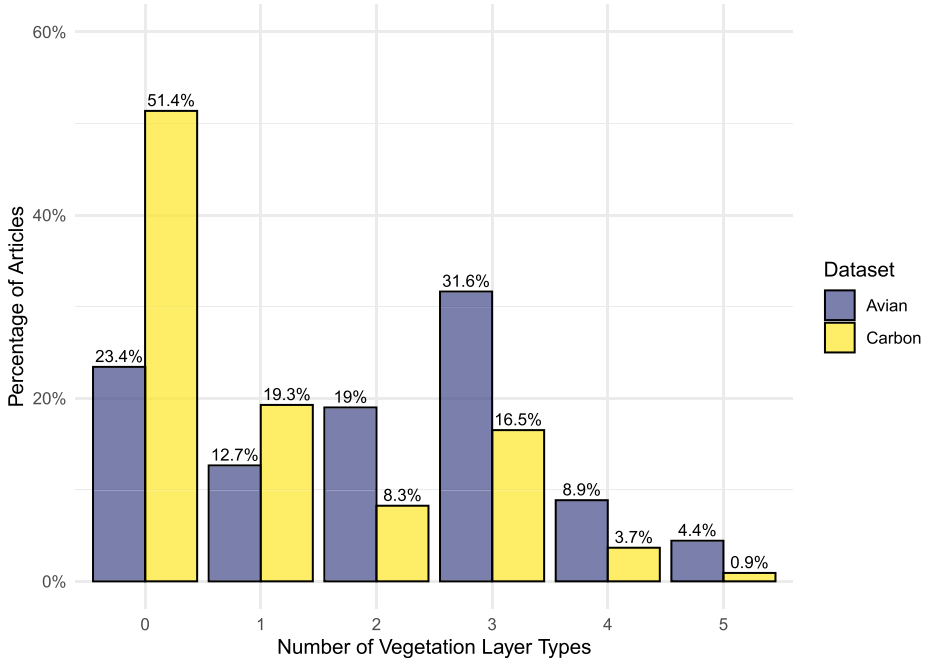


Figure 2. The number of vegetation layer type metrics studied per article in carbon ($n = 109$) and avian ($n = 158$) extracted from urban forest research articles in a systematic literature map (Hutt-Taylor *et al* 2024). Vegetation layer types consist of tree, shrub, ground, vine, leaf litter, and coarse woody debris layer. Articles that did not explicitly assess the presence and/or cover of any of these vegetation layer types were considered to have measured zero layers, even if they measured some other characteristic of that type of vegetation (e.g. tree density).

articles more frequently used tree crown measurements (i.e. crown width/area and crown height), while diameter and total height were more evenly used in both bodies of literature. Beyond assessing the presence or extent of the tree layer, variables related to structural and vegetation layer types were more common in avian articles. Tree characteristic metrics directly related to specific features (i.e. cavities, fruit, perch/nest height) were exclusive to avian articles.

3.2. Dominant vegetation layer types studied

In general, articles studying avian outcomes of urban forest management considered more vegetation layer types than those studying carbon outcomes (figure 2). More than half of carbon outcome studies failed to include a single composition metric related to vegetation layers, while less than a quarter of the avian studies did the same (figure 2). In fact, while it was most common for carbon outcome studies to include no vegetation layer metrics, the most common combination for avian research was to consider three metrics concurrently (>30% of avian papers, figure 2). Tree, shrub, and ground layers were the top three considered by both, though considered in higher proportions by avian articles than carbon (figure 1). Vine layer appeared only in the avian group ($n = 2$), and leaf litter and coarse woody debris were uncommon in both, but especially uncommon in carbon studies (supplementary material figure S3).

3.3. Specific measures of avian success and carbon outcomes

We related the use of each forest composition metric with the specific type of carbon- or avian-related outcome measured in each article (coded in the (Hutt-Taylor *et al* 2024) database). Both carbon (figure 3) and avian (figure 4) groups present clear trends where most studies examine primarily one type of outcome (i.e. aboveground biomass or avian biodiversity, respectively) but use several composition metrics in similar frequency to do so.

3.4. Co-occurrence of metrics using Jaccard similarity index

We calculated Jaccard similarity index (J), which measures pairwise co-occurrence of values, for all composition metrics in the carbon and avian groups (excluding metric self-comparisons). Among carbon studies, the 190 metric pairs showed relatively low co-occurrence (median $J = 0.11$, mean $J = 0.16$), ranging from 0.00 to 0.90 (highest co-occurring pair was diameter and tree species composition; figure 5). Avian studies had somewhat lower co-occurrence across their 276 metric pairs (median

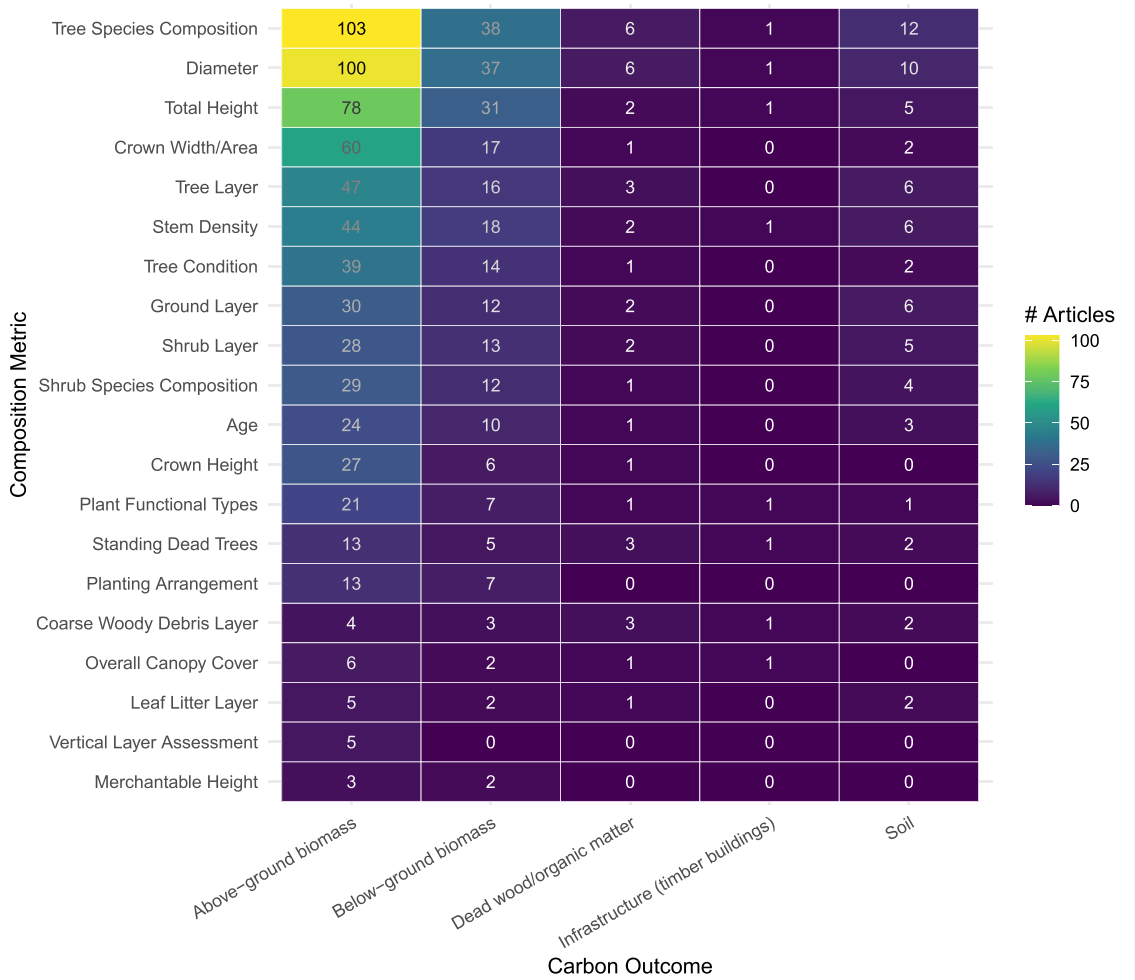


Figure 3. Frequency of use of different forest composition metrics by carbon outcome (see table 2 for definitions) from articles assessing carbon outcomes ($n = 109$) extracted from urban forest research articles in a systematic literature map (Hutt-Taylor *et al* 2024).

$J = 0.06$, mean $J = 0.11$), ranging from 0.00 to a maximum of 0.77 (highest co-occurring pair was shrub layer and tree layer; figure 6). While there was low co-occurrence overall, both groups had certain pairs of metrics with substantially higher co-occurrence than the rest.

4. Discussion

We provide evidence of both overlap and divergence of forest composition metrics used in research on climate change mitigation (carbon) and biodiversity conservation (avian) outcomes in urban forest management. Generally, we found greater similarity across forest composition metrics used in research on carbon outcomes, with several metrics being found almost ubiquitously across all papers. Forest composition metrics on carbon outcomes were most often those related to size, structure, and certain tree characteristics. In comparison, forest composition metrics associated with research on avian outcomes of urban forestry management were more diverse, with a lack of common metrics found across almost all studies. Avian outcome papers also examined or quantified metrics that were unique to this literature group, such as specific tree characteristics (e.g. presence of fruit or cavities), and focused much more on the presence of one or often more vegetation layers in urban forests. Overall, our findings raise several important questions for planning and management of urban forests to address climate change and biodiversity loss simultaneously. Which metrics should future urban forest monitoring or data collection efforts include to more fully assess carbon and avian outcomes? Are there composition metrics that relate to avian or carbon metrics that lend themselves more to assessing together? And, fundamentally,

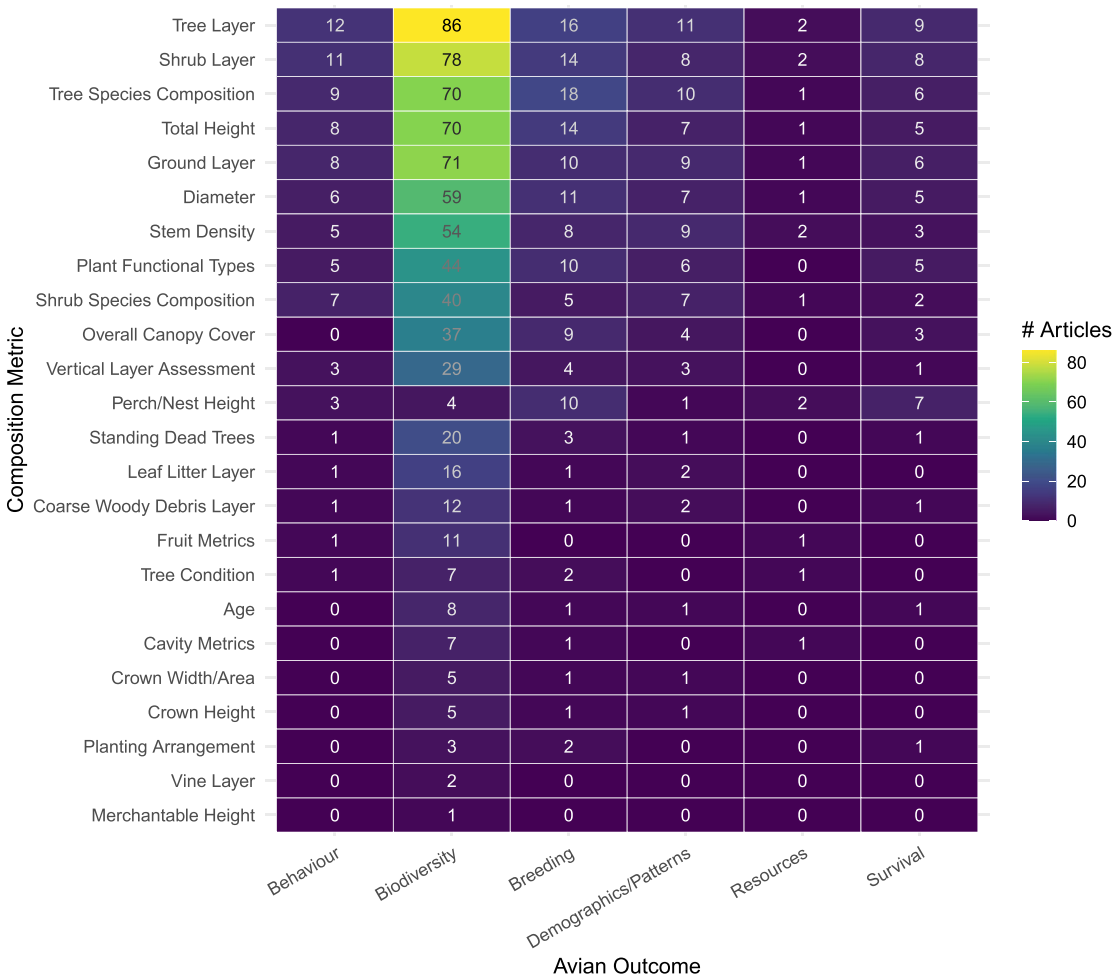


Figure 4. Frequency of use of different forest composition metrics by avian outcome (see table 2 for definitions) from articles assessing avian outcomes ($n = 157$, one avian article was only about cavities which could be used as nests and thus did not have a coded avian success outcome) extracted from urban forest research articles in a systematic literature map (Hutt-Taylor *et al* 2024).

which metrics have positive relationships with both carbon and avian outcomes—or, where can the most synergies be found in management?

Our findings on the near universal use of certain metrics in the carbon studies (e.g. tree species composition and diameter) likely reflects the standardized requirements of allometric biomass models needed to estimate carbon storage and sequestration (McPherson *et al* 2016) and is further supported by the high co-occurrence of these variables in the Jaccard analysis (figure 7). In contrast, avian studies lacked a dominant set of metrics; the top two most frequent measures were assessments of simple presence or extent of a tree layer and shrub layer. Tree species composition was only assessed in 54.4% of avian articles, perhaps a reflection of a higher important of tree functional groups or other characteristics than exact species for assessing avian populations (Wood and Esaian 2020) compared to the significance of species for carbon sequestration and storage. The differences in recording of tree species could also perhaps reflect the difficulty in leveraging the specialized expertise and significant time necessary for both bird monitoring and tree species identification (though shrub species composition was recorded at near equal frequency). Additionally, more avian studies considered plant functional types than carbon studies, perhaps as a substitute for considering specific species composition (e.g. deciduous vs evergreen). There are also issues in reconciling scale of measurement, for example, a majority of bird surveys, particularly in forests, are performed at specific points or aurally (Brewster and Simons 2009) while vegetation characteristics in avian studies may be measured at the patch or landscape-scale, such as via tree canopy or land cover datasets, and not always for individuals trees (with notable exceptions for cavity-nesting birds (Martin *et al* 2004) or behavioral studies (Wood and Esaian 2020) where the objective may be to record how the birds interact with a tree via nesting or perching).

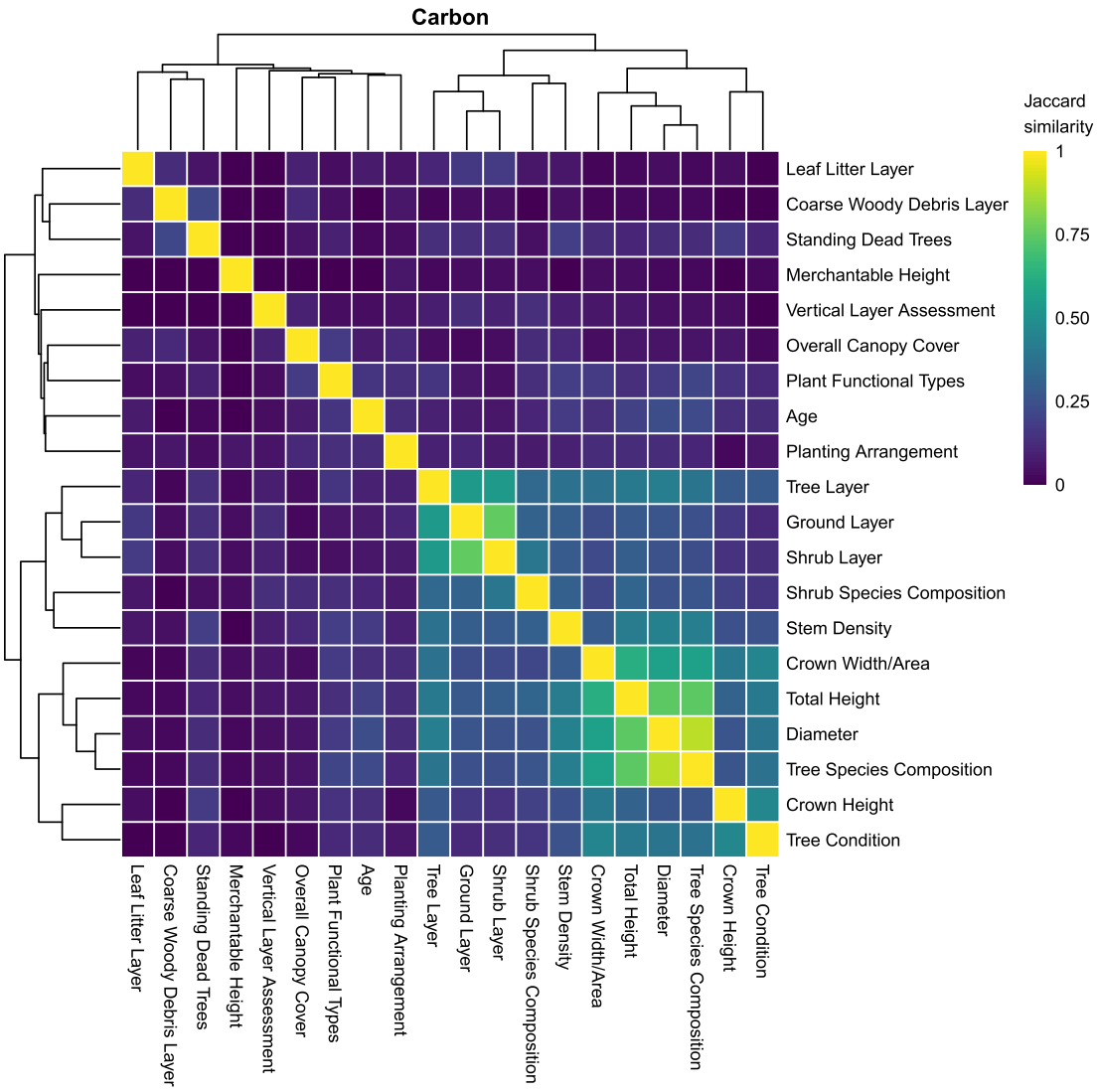


Figure 5. Co-occurring urban forest composition metrics across studies assessing carbon outcomes ($n = 109$) extracted from urban forest research articles in a systematic literature map (Hutt-Taylor *et al* 2024). Heatmap and dendrograms of Jaccard similarity index.

4.1. Gaps, challenges, and opportunities for integrative monitoring in urban forests

Despite the several clear points of divergence in our results in forest composition metrics between carbon and avian literature, the overlap in their most frequently used metrics indicates that there is potential for more integrative monitoring of carbon and avian outcomes in urban forests. Of the top six most-used composition metrics (figure 1), the carbon and avian groups shared four in common: diameter, total height, tree layer, tree species composition. Indeed, these same metrics are core, often minimum, components of standard urban forest monitoring frameworks (Roman *et al* 2020, Edgar *et al* 2021). Many of the carbon studies we assessed employed standard urban forest assessment protocols, like i-Tree Eco (Nowak *et al* 2008), while in contrast, avian studies often employed site-specific study design and methodologically diverse metrics (Jones 2001, Dudley and Saab 2003). Measuring avian outcomes like behavior or nesting status require even more specialized expertise, as well as significant time, effort, and knowledge of seasonal trends, to record accurately—perhaps explaining why most of the reviewed studies considered biodiversity measures (e.g. species counts) to assess avian outcomes (figure 4). Nonetheless, there are established avian monitoring protocols (Knutson *et al* 2016, Mclaren *et al* 2025) and new efforts to develop urban-specific wildlife monitoring protocols (Magle *et al* 2019) which could be used in designing future integrated monitoring efforts. This may also need further cooperation across departments/agencies and research groups which are typically siloed between nature resource management vs. wildlife management goals (Hutt-Taylor *et al* 2025). Given our results, we suggest that synergies in managing urban forests for carbon and avian diversity could increase if carbon researchers measured

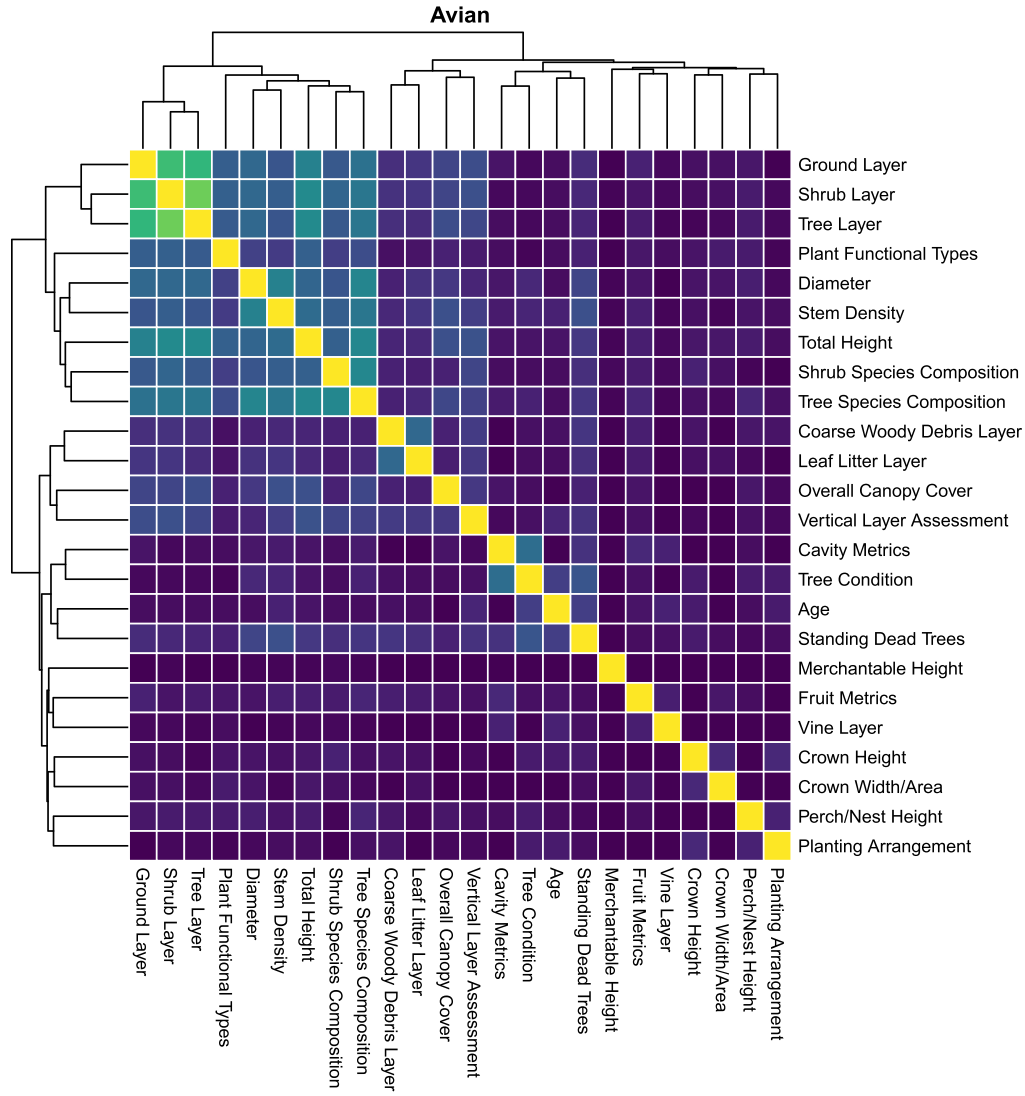


Figure 6. Co-occurring urban forest composition metrics across studies assessing avian outcomes ($n = 158$) extracted from urban forest research articles in a systematic literature map (Hutt-Taylor *et al* 2024). Heatmap and dendrograms of Jaccard similarity index.

vegetation layer metrics (presence or extent of not just tree, but also shrub, and ground layers) and avian researchers measured size metrics (diameter, total height, crown width/area) more frequently. Future research investigating the relationships between these metrics and the strength and direction of carbon and avian outcomes could also identify new, synergistic management strategies.

From our analysis of the existing research on relationships between urban forest composition and carbon and avian outcomes, we can describe the scope of what has been published thus far and identify patterns in metric use. However, we are limited in that the analysis of the dataset our articles were extracted from (Hutt-Taylor *et al* 2024) was designed to broadly map the state of the field. These results can be used to highlight areas and relationships for future research and monitoring, yet, as it was beyond the scope to assess the quality of individual studies or the strength and direction of relationships between metrics and outcomes, we cannot definitively determine which metrics are most effective predictors of carbon or avian outcomes. However, there have certainly been some notable studies using empirical findings to model the impact of forest composition metrics on carbon and avian outcomes (e.g. Lerman *et al* 2014, Drolen *et al* 2023).

4.2. Linking urban forest composition metrics with management outcomes in future research

To drive application of these results in practice, future research could also investigate the 'manageability' of different metrics. We focused this study on urban forest composition as a representation of variables which could be more influenced by management than say geography or land cover, nonetheless,

this is easier said than done. Not all commonly measured attributes are equally responsive to management interventions. For example, species and size distributions at population levels can be influenced over long time horizons through planting and retention strategies (Nagendra and Gopal 2011, Nitoslawski *et al* 2016, Lindenmayer and Laurance 2017), while shrub layer presence in specific areas could be altered quickly and cheaply through planting or maintenance practices. There are also potential pitfalls to watch out for. For example, while large trees may contribute disproportionately to aboveground biomass (Piponiot *et al* 2022, Drolen *et al* 2023), and may also significantly correlate with bird populations (Kebrle *et al* 2021, Komlós *et al* 2024), promoting only size-based metrics may inadvertently reduce habitat heterogeneity if not paired with strategies to maintain understory and midstory layers. Finally, the likelihood of being able to manage urban forests for these outcomes are dependent on not just resources available to local and regional governments, but in the objectives and values of all actors managing trees across urban areas (Cadaval *et al* 2024, Doucet *et al* 2024). There is evidence in the face of these complexities of multi-objective management that urban forest managers may potentially default to strategies focused on increasing urban forest health and extent in general (Bassett *et al* 2025).

Looking ahead, the state of urban forest assessment is likewise changing due to advancements in analysis of remote sensing and LiDAR (Fry *et al* 2025). While certain variables may have lent themselves to easier collection in the field and thus be represented heavily in past studies, it could become easier and faster to obtain measurements of tree composition at larger scales (Li *et al* 2019, Maeda *et al* 2025), for example using cell phone-equipped devices or LiDAR remote sensing instead of calipers or diameter tapes (Gülci *et al* 2023, Magnuson *et al* 2024). Datasets and methodologies to assess avian outcomes are also advancing, such as through bioacoustic monitoring networks (Pérez-Granados and Traba 2021) and participatory science (McCaffrey 2005, Sullivan *et al* 2014). While new datasets represent enormous opportunities to uncover relationships, coordinated data and monitoring frameworks will still require cross-disciplinary approaches to fully understand implications for management.

5. Conclusion

Overall we found both significant commonalities, and substantial differences, in how researchers study urban forests for climate mitigation (carbon) and biodiversity conservation (avian) outcomes. While studies employed mostly the same set of metrics (20/24), studies assessing carbon more often used a more restricted set of core variables, while studies assessing avian outcomes employed a broader, more specialized set of metrics. Reasons for this difference may be disciplinary siloing of knowledge and skills, limited time and resources for data collection, difference in scale of interest, and difference in required inputs for ecological models. Developing shared monitoring frameworks for both climate mitigation and biodiversity conservation outcomes for urban forestry management is theoretically feasible, especially given the overlap in metrics commonly used to study both outcomes. Enabling data collection that would overlap forest composition metrics for both outcomes could facilitate greater knowledge transfer and meet the critical needs of land managers tasked with multiple goals. To enact this in practice would undoubtedly take effort and collaboration, and modification of existing monitoring protocols and norms. Without further alignment in measurement approaches, opportunities to identify synergies or tradeoffs between carbon and biodiversity outcomes may be missed.

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Data availability statement

The data that support the findings of this study are included in the supplement. The code used to conduct the analysis is openly available at the following URL: https://github.com/zule-lab/UFCompMetrics-Carbon-Avian.

The data that supports the findings of this study are openly available in the supplementary files of this article.

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Conflict of interest

The authors have no conflicts of interest to report.

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