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Understanding Opportunities for Urban Forest Expansion to Inform Goals: Working Toward a Virtuous Cycle in New York City

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Abstract

Urban forests are critical infrastructure for mitigating environmental and social challenges cities face. Municipalities and non-governmental entities, among others, often set goals (e.g., tree planting or canopy targets) to support urban forests and their benefits. We focus on canopy goals and develop conceptual underpinnings for an analysis of where additional canopy, as one important dimension of the urban forest, can fit within the landscape, while considering factors that influence where trees can be planted and where canopy can grow – 'practical canopy.' We apply this in New York City (NYC) to inform the setting of a canopy goal by the NYC Urban Forest Task Force (UFTF) for the *NYC Urban Forest Agenda*, which may trigger a *virtuous cycle* that supports the urban forest there. We further develop framing for a 'priority canopy' analysis to understand where urban forest expansion should be prioritized given more context (e.g., environmental hazards, local preferences), which can inform how expansion of the urban forest is achieved. We estimate an opportunity for 15,899 ha of new canopy in NYC given existing opportunities and constraints (practical canopy), which, if leveraged, could result in nearly doubling the canopy as of 2017 (17,253 ha). However, like existing canopy, practical canopy is not evenly distributed, in general, or across jurisdictions and land uses. Relying solely on areas identified as practical canopy to expand the urban forest would exacerbate inequities in its distribution. We discuss how the NYC UFTF established an aspirational but achievable goal of 30% canopy cover by 2035, which was informed by this analysis and guided by priorities of equity, health, and resilience. Achievement of this goal will ultimately require a combination of protecting and stewarding the existing resource, and leveraging opportunities for tree planting. Achieving a more equitable urban forest will also require identification of priority canopy, and, in cases, creation of new opportunities for tree planting and canopy expansion. Overall, the collaborative establishment of such goals based on local context can be instrumental in creating a *virtuous cycle*, moving conservation actors toward exercising influence and agency within the social ecological system.

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1 Introduction

Urban forests are complex systems that include all trees in a city and the physical and social infrastructure on which they depend (adapted from Robertson and Mason, 2016). They also serve as critical infrastructure for mitigating various social and environmental challenges cities face. For example, urban forests help reduce the urban heat island effect (Alonzo et al., 2021), they support management of stormwater runoff (Selbig et al., 2022), and they are both comprised of and are habitat for various animal and plant species (Derby Lewis et al., 2019). Further, benefits of urban forests including air quality improvement (Lai and Kontokosta, 2019), carbon sequestration (Nowak et al., 2013; Pregitzer et al., 2022), community cohesion (Campbell et al., 2016; Svendsen et al., 2016), and mental well-being (Berman et al., 2021), among others, are increasingly demonstrated and understood. Despite the increasing recognition of the roles that urban forests play, recent work indicates they are declining throughout the United States (Nowak and Greenfield, 2018). However, intentional planning for and maintenance of urban forests can help sustain and expand them through the long term (Dwyer and Nowak, 2003). Targeted planning of the resource with engagement of stakeholders can ultimately set off a virtuous cycle, or a self-reinforcing feedback loop in which acting for the conservation of the resource ultimately supports its long-term conservation through ongoing commitment (Morrison, 2016).

One way that municipalities, non-governmental entities, stewardship organizations, and collaborative groups or coalitions support planning and maintenance of urban forests is by setting goals to maintain or expand them and their benefits. These goals are often set within one of two frames –as tree planting targets, through which a number of new individual trees is set for planting, or tree canopy cover targets, which aim to increase the cumulative land area covered by leaves and branches of trees (Raciti et al., 2006; McPherson and Young, 2010). While tree planting goals can be galvanizing, particularly shortly after they are established (Eisenman et al., 2021), they alone do not account for factors such as ongoing loss or removal of trees, or for the ongoing management needs of existing trees that support canopy expansion through time. They functionally only consider one element of a dynamic system, and may not, in and of themselves, capture net effects of overall management of the urban forest (McPherson and Young, 2010). Achieving and maintaining a specific canopy cover ultimately requires holistic management of the urban forest that considers the life cycle of trees, including tree protection and care, in addition to planting (e.g., see the Chicago Region Tree Initiative 2050 Master Plan; Morton Arboretum, 2018). Further, the holistic nature of a canopy goal can more directly tie to benefits –benefits of individual trees may be difficult to calculate and track (depending on species, size, local context, and other factors), particularly while accounting for trees removed, though benefits such as urban heat amelioration (Ziter et al., 2019) and stormwater management associated with interception of precipitation can be closely associated with canopy cover. Given these considerations, we focus on urban forestry goals for canopy rather than tree planting targets.

Even when urban forestry goals may be achievable, it is important that they respond to local constraints and opportunities to realize desired benefits. For example, factors such as residents' demand for or interest in trees and their benefits, soil conditions, and availability of resources for maintenance can play important roles. This insight was gleaned from experience of urban foresters, researchers, and community members, and informed a transition by American Forests (a leading urban forestry organization) away from a universal recommendation of 40% canopy cover in cities (Leahy, 2017). The updated guidance came after more nuanced methodologies and processes to set canopy goals had been developed, including the "Three P's" (Raciti et al., 2006): (1) the "possible canopy," which answers the question, "Where is it biophysically feasible to plant trees?"; (2) the "potential canopy," which answers, "Where is it economically likely to plant trees?"; and, (3) the "preferable canopy" which answers, "Where is it socially desirable to plant trees?" Answering the questions embedded within the three P's, as well as identifying where trees already are, can support the community of people and organizations that plan for and manage the urban forest (Raciti et al., 2006). The concept of "possible canopy" has been applied in myriad municipalities (often cities and broader counties) including in: New York City (NYC), New York (Grove et al., 2006; O'Neil-Dunne, 2012); Philadelphia, Pennsylvania (O'Neil-Dunne, 2011, 2019); and Charlotte and Mecklenburg County, North Carolina (O'Neil-Dunne, 2014). There are important examples of advancing beyond that, toward "preferable canopy" and prioritization schemes for new canopy (Locke et al., 2010, 2013), though efforts to refine mapping of where new canopy can go, and grounding prioritization in more localized needs, have been limited.

A combination of the natural history and landscape context of cities, and the historic priorities and decisions of institutions and communities of people affecting land use, have contributed to the current urban forest in a given city (Roman et al., 2018). In particular, the natural history of a city has implications for the characteristics of the urban forest that the city might strive for. For example, in Phoenix, the vision for its urban forest is one that "reflects and preserves the beauty of the Sonoran Desert," focusing on local species such as palo verde (*Parkinsonia florida*), ironwood (*Olneya tesota*), and mesquite (*Prosopis* spp.), with a 25% tree canopy cover goal by 2030 (City of Phoenix, 2009). In contrast, in subtropical, humid Louisville, Kentucky, a goal of 45% canopy cover was set to aggressively combat trends of tree loss and ongoing risks, particularly for ash trees (*Fraxinus* spp.), identified in local research efforts (Louisville-Jefferson County Metro Government, 2015). In some cases, local stakeholders may also decide areas are not appropriate for urban forestry because of their natural history. For example, in NYC, the master plan for the reclamation of the Fresh Kills Landfill ultimately prioritized restoring tidal marshes to the area (Field Operations, 2006).

While natural history provides a lens for ecological opportunities and constraints, decisions about a city landscape are ultimately influenced and made by people and institutions with varying priorities and levels of both direct and indirect influence. The distribution of tree canopy thus often reflects legacies of historic policy, land use, and sometimes socially exclusionary efforts, which had influence on the urban forest. For example, in United States cities, tree canopy is often less prevalent in areas that were historically the subject of discriminatory lending practices, such as "redlining," which codified neighborhood demographic make-up as a determinant for default risk on property loans (Locke et al., 2021). The result of redlining was systemic disinvestment in immigrant (particularly Mexican, Jewish, and Asian), poor, and, especially, Black (including Black Latinx) neighborhoods, as residents were less able to attain loans and mortgages from banks (Woods, 2012). Further, in many areas it was common to add racially restrictive covenants in property deeds that prohibited the sale of homes to people of color (Nardone et al., 2021). Thus, people of color have had limits, beyond economic, in where they can purchase property, sometimes keeping them in the redlined areas that not only tend to have less tree canopy (Locke et al., 2021), but also have less vegetation overall (Namin et al., 2020), and are significantly hotter (Hoffman et al., 2020). Variation in conditions within a city can also be associated with zoning and land use (e.g., see Maantay, 2002, 2007), and highlights the need for place-specific investigation of social and development histories that have shaped the current landscape. For example, in NYC, while there is lower tree canopy cover in redlined areas in four out of the five boroughs, there is no discernable trend in Manhattan, where lower tree canopy tends to be associated with higher incomes (Treglia et al., 2021a). Such variation may be the result of varying development histories across the five boroughs, as Manhattan is historically more densely developed as a whole and there is not much variation in tree canopy across most parts of the borough. Nonetheless, benefits from an expanded urban forest can have the greatest positive impact in neighborhoods with socially vulnerable residents (Zhou et al., 2021). Such expansion of the urban forest can be driven by current priorities, but aspects of it may be influenced by historic factors that set forth constraints in the contemporary landscape, such as where there is pavement, underground utilities, and land uses or built features that may conflict with trees, their roots, or their canopy.

Ultimately, understanding natural and social context can help guide setting and implementation of urban forestry goals. In support of that, herein we develop the concept of 'practical canopy,' a data-based analysis that identifies where new canopy can likely fit within a given landscape, to inform setting of tree canopy goals while accounting for local context – particularly factors that affect where trees may be planted and where canopy can grow. We also propose a subsequent step, mapping of 'priority canopy.' This step goes beyond the question of what opportunities *currently* exist to develop a better understanding of where expansion of the urban forest is locally desired or needed, which can indicate, in some cases, that landscape change is required to achieve these priorities. We build on existing approaches, incorporating elements from all "Three P's" (Grove et al., 2006; Raciti et al., 2006). We then describe our effort to map practical canopy in NYC to support development of a canopy cover goal by the collaborative stakeholder group, the NYC Urban Forest Task Force (UFTF), for inclusion in the *NYC Urban Forest Agenda* (NYC Urban Forest Task Force, 2021). In the past, while at least one canopy goal had been proposed, 30% by 2030 (from 2006) based on analysis of "possible canopy" (Grove et al., 2006), a tree planting goal (of one million trees within 10 years) was ultimately adopted as part of a mayoral initiative, PlaNYC (Campbell, 2017). The mapped practical canopy is not intended to be prescriptive of where trees should be planted or canopy should be added, or how a canopy goal should be achieved. Instead, it is one step in creating a *virtuous cycle* (Morrison, 2016). The development and results of the practical canopy analysis engaged stakeholders directly by providing information asked for in the process of setting a tree canopy goal, and moved the UFTF toward exercising agency in the social ecological system by requiring explicit articulation of values and objectives.

In mapping practical canopy, we sought to answer: 1) *How much opportunity for additional tree canopy do we estimate exists in the current NYC landscape*? 2) *How does this vary by geographic scale, jurisdiction, and land use*? and 3) H*ow does the practical canopy compare to existing and "possible" canopy* (*sensu* Grove et al., 2006; Raciti et al., 2006)? Further, we describe how this information supported discussions about potential to expand the urban forest in ways that address existing inequities, a priority identified by the NYC UFTF, which led to their setting of a 30% tree canopy cover goal by 2035 for NYC as part of the *NYC Urban Forest Agenda*. The hope is this process has set forth a virtuous cycle that continuously brings in more actors – including policymakers and those immediately affected by the resource – who strive to maintain and expand the urban forest across temporal and spatial scales for its intrinsic value and its benefits, and ultimately the sustenance of a self-supporting social-ecological system.

2 Methods

2.1 General Definitions and Processes of Mapping Practical Canopy

We define practical canopy as the spaces or areas within a landscape where it is estimated that new tree canopy can be grown from newly planted trees (or potentially existing ones), while accounting for constraints associated with land use, land cover, and built infrastructure. Mapping practical canopy assumes such constraints are static (i.e., unchanging in the foreseeable future), with analysis based on spatial data (raster or vector) that represent the landscape at a point in time or under different scenarios (e.g., with future development scenarios modeled). Further, it requires those

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involved in the work (e.g., researchers, managers, advocates) to make assumptions or decisions about how features on the landscape can functionally constrain planting of new trees and expansion of canopy (e.g., athletic fields would generally be considered as having a conflicting land use, and tall buildings could physically limit where tree canopy can grow). It is ultimately intended to offer insight into how much new canopy a landscape may accommodate in its current form. Mapping of practical canopy is not intended to be prescriptive in terms of where new canopy should be added, as it is a spatial model that does not necessarily resolve conflicting values, or incorporate local perspectives, all constraints at play, and the potential to change the landscape in ways that can create new opportunities for canopy or tree planting (by, for example, de-paving land). However, it can support conversations about these factors.

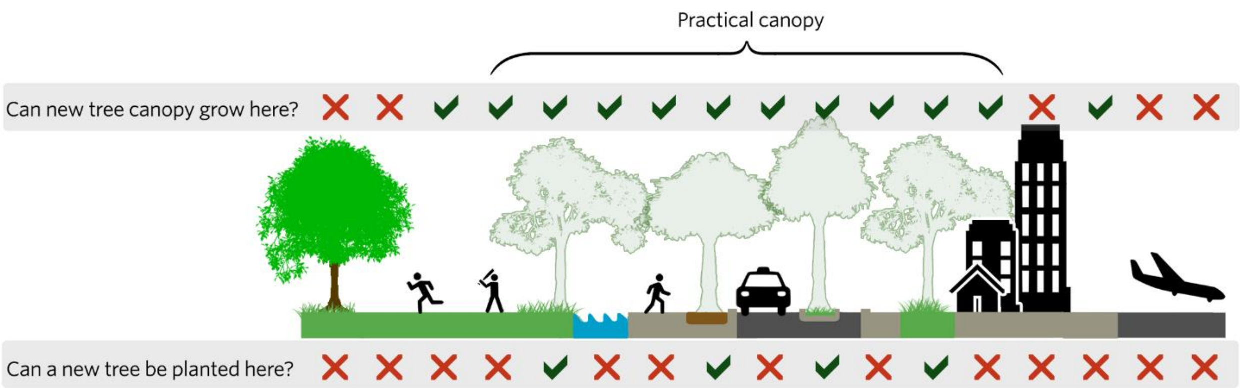

Figure 1. Diagram illustrating the general concept of how practical canopy is considered across the landscape, including whether trees can be planted given features on the ground, whether canopy could occur or would be allowed to occur (e.g., canopy from trees at grade would not be tall enough to overlap tall buildings, and may not be allowed to exist in certain portions of airports). Practical canopy is ultimately the canopy that could be grown given the combined consideration of where trees can be planted and grow. Note – the opaque tree depicts an existing tree; the transparent ones represent hypothetical trees that could be planted and would contribute to realization of practical canopy.

Mapping practical canopy entails three general steps that rely on spatial data for the focal area and assumptions for where new trees can be planted and where canopy could exist in the spatial model (termed “allowability” for planting and canopy; Figure 1).

1. **Delineate *planting allowability*, or where within the landscape trees can likely be planted**. This involves developing assumptions of what types of land use and land cover are suitable for tree planting, and applying them to relevant spatial data (it is then assumed that canopy could cover these spaces).
2. **Delineate *canopy allowability*, or where within the landscape tree canopy could likely exist**. This involves developing assumptions of where tree canopy would not conflict with other land use, land cover, or built environmental features in the landscape and applying them

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to the spatial data. This does not account for whether trees could be planted near those spaces but is framed as 'if trees exist nearby, could canopy grow to fill the space?'

3. **"Grow" tree canopy from spaces considered allowable for planting (and potentially from existing canopy), constrained to areas delineated as allowable for canopy.** The maximum amount that canopy is grown can be specified based on additional assumptions regarding how large trees may be anticipated to grow.

While practical canopy mapping can be conducted for an entire city based on a holistic set of data and assumptions, it can also be stratified to incorporate unique assumptions for different geographic units or land use, zoning, and jurisdiction, among other characterizations.

2.2 Mapping Practical Canopy in New York City

2.2.1 Creating a Baselayer: Processing Land Cover & Land Use Data Layers

We combined a suite of relevant data layers related to where trees can likely be planted (planting allowability) and where canopy could theoretically exist (canopy allowability) in the current landscape into a single data layer, hereafter referred to as the 'baselayer' (the full list of data layers used is available in Supplementary Materials). The baselayer was developed primarily from a suite of planimetric layers reflecting features across the landscape including building footprints, roadbeds, medians, sidewalks, parking lots, and recreation fields, among others, as two-dimensional polygons. We retained information associated with these data layers as needed – for example, we included estimated building height from the building footprint layer, useful in setting canopy allowability. While individual properties were not wholesale included in the baselayer, we included boundaries of particular types for which we specifically delineated planting and canopy allowability (e.g., airports, community gardens). Further, we masked out areas considered natural, as areas for which canopy is not necessarily appropriate given ecological context and management goals. We did this based on a data layer from the NYC Department of Parks and Recreation (NYC Parks) for properties managed by that agency (the Dominant Type dataset), and an ecological covertype map from the Natural Areas Conservancy (O'Neil-Dunne et al., 2014) for the rest of the landscape. For informing the discussion of practical canopy with the NYC UFTF, staff from NYC Parks and the Natural Areas Conservancy provided estimates of potential for new canopy in the near term for these spaces within City-owned land as an aggregate (i.e., not spatially explicit), suggesting a relatively small area of canopy (81 ha) may be added to these spaces as a result of natural processes (e.g., succession) or planting in the next 10-15 years.

All datasets included in the baselayer were the most recent available (spanning 2010-2021) and represented an approximation of the landscape at the time of analysis. Many of the datasets originated from a set of planimetric data based on digitization of aerial imagery from 2014, though we supplemented more recent data as available, such as of building footprints and landscape elements within NYC Parks' jurisdiction. We augmented data on roads based on spatial joins between roadbeds and a regularly updated line dataset of roadways maintained by the City government.

We generally used the spatial data as obtained from the various sources, with two main exceptions (detailed data processing steps and list of data used are available in Supplementary Materials). First, airports were treated as a special case, as there are often height restrictions that extend beyond their boundaries (e.g., per Zoning Resolution of the City of New York, 1993). Thus, we manually extended the boundaries of the two active airports in NYC, based on input from partners who have experience in this realm and visible patterns of limited trees along flight lines in aerial imagery. Second, boundaries of recreation fields often only encompassed actual playing surfaces (or even a

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subset, such as the infield diamond of a baseball field), and did not include other, adjacent, actively used spaces such as where players sit. We examined myriad examples of these data with aerial imagery and after consultation with local experts, we buffered recreation fields by 30.48 m (100 ft) before incorporating them into the baselayer to account for such limits of these data. All data used were downloaded in or reprojected to a common coordinate reference system, EPSG 2263 (New York State Plane, Long Island Zone (ft), NAD 83), which supports accurate area calculations for the focal area. Spatial data were processed using a combination of ArcGIS Pro version 2.8 (Esri Inc., 2021), PostgreSQL version 13.0/PostGIS 3.1 (PostGIS Project Steering Committee, 2021; The PostgreSQL Global Development Group, 2021), and QGIS version 3.12 (QGIS.org, 2020).

2.2.2 Defining Planting and Canopy Allowability

For each layer we incorporated into the baselayer, we considered whether the areas represented could likely support new trees being planted (with canopy growing directly above those spaces; 'planting allowable'), new tree canopy overhanging ('canopy allowable'), or neither (see Figure 2A-2B). Our intent was to approximate where new trees and their respective canopy could be added to the landscape while avoiding fundamental conflicts with current land use (e.g., active recreation fields) and landcover (e.g., avoiding existing canopy) and infrastructure (e.g., canopy generally cannot extend atop taller buildings). A list of the types of polygons present in the baselayer and the designation assigned for planting and canopy allowability can be found in Supplementary Material.

We considered spaces as not allowable for tree planting when:

- Tree planting would, in general, be implicitly incompatible with the use of, or the infrastructure in the space, as discernable in the available data. For example, spaces encompassed within building footprints, active recreation fields, roadbeds, and water bodies were not considered "allowable" for tree planting in our analysis.
- Logistics or regulations are generally understood to substantially constrain tree planting in certain parts of the landscape with specific land uses, histories, or infrastructure, such as airports and landfills. Cemeteries were also included in this category; while some cemeteries have canopy cover and are managed in part to maintain trees, management practices and logistical constraints can vary widely and thus we erred on the conservative side in this case.
- Ground level surfaces were estimated to be paved in any way, given that there is often substantial work required to make the space suitable for planting a tree (albeit see section on street trees below). Recognizing trees require some space to even be planted, non-paved areas were required to be a minimum area of 2.32 m^2 (representing a small tree bed).

We considered spaces as not allowable for additional canopy on the landscape when:

- Infrastructure such as tall buildings that trees would generally not be tall enough to overhang were present (set at 10.67 m; see Supplementary Material for details on how this threshold was set).
- Clear lines of sight and unplanted areas are required as standard procedure to manage things like risk associated with downed branches, (e.g., over travel and shoulder lanes of highways).
- Overhanging canopy may conflict with the primary use of a space (e.g., community gardens that rely on sun exposure for fruit and vegetable production).
- There is existing canopy.

This delineation of allowability for planting and canopy was conducted for the entirety of NYC, excluding natural areas (beyond the scope of the effort described herein) and sidewalks in rights of

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way, where street trees could be planted (treated uniquely, per the section: *Estimating Planting Allowability for Street Trees*).

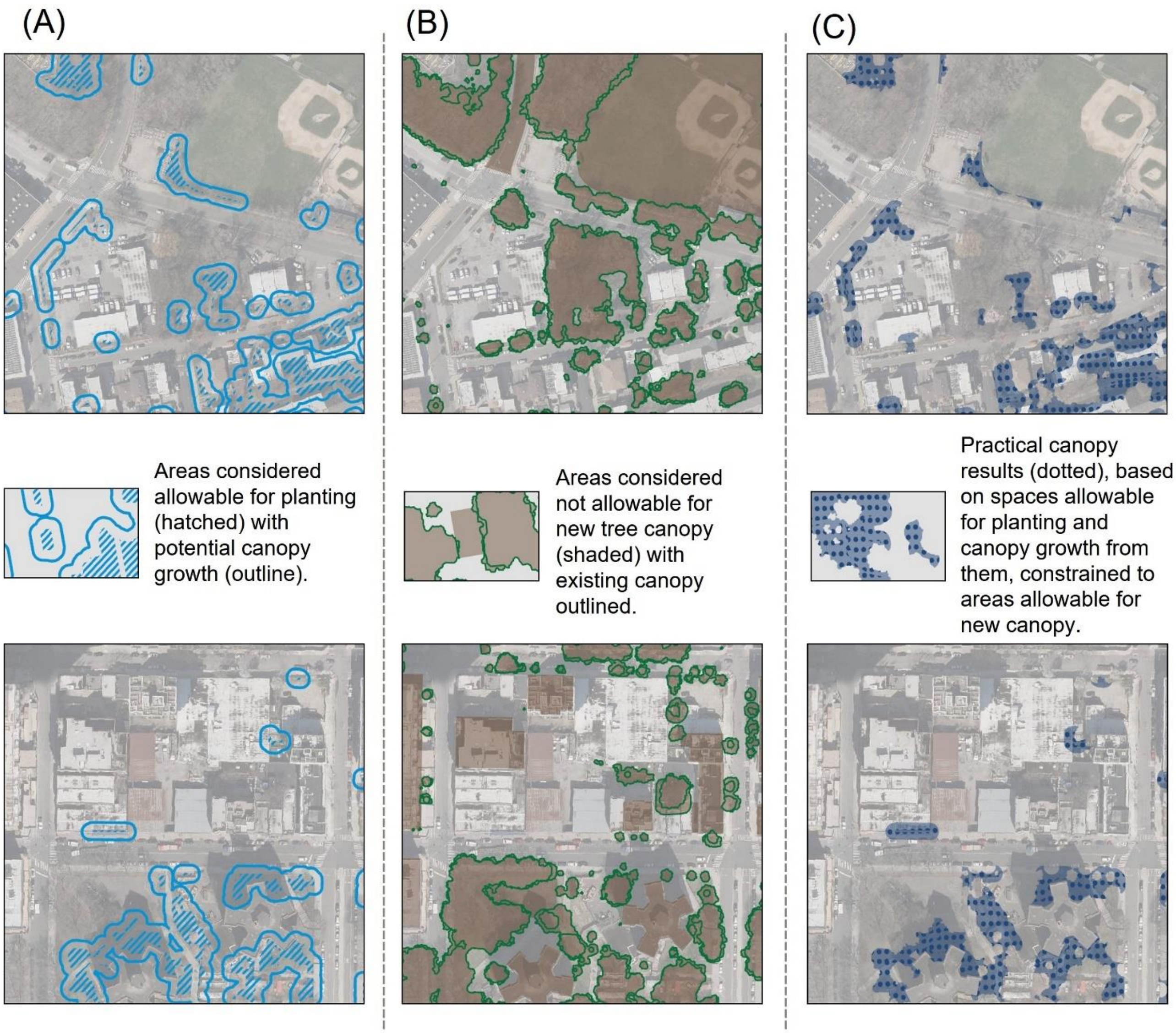

Figure 2. Illustrative maps representing the process of mapping practical canopy in New York City, including delineation of where the landscape was considered allowable for tree planting (A), where the landscape was considered allowable or not for canopy (B), and how the two were used together to map practical canopy (C). The concepts apply the same in the top and bottom images, but in areas of the landscape with different levels of development and complexity. Imagery is courtesy of the City of New York, Department of Information Technology and Telecommunications.

2.2.3 Estimating Planting Allowability for Street Trees

Street trees in NYC are trees associated with public surface streets, typically planted along sidewalks, under the jurisdiction of NYC Parks. They were considered separately from other trees because they

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are subject to specific rules regarding where they can be planted due to their potential impacts on intersections, sidewalks, and existing street trees documented in the *Street Tree Planting Standards for New York City* (City of New York, 2016). Per these rules, a street tree should generally be planted: (1) a minimum of 6.10 m away from another street tree; and, (2) a minimum of 12.19 m from the corner of a road intersection (City of New York, 2016). To simulate new street trees, we used the baselayer in conjunction with data from the most recent (2015-2016) street tree census, to assign areas that comply with these rules as 'planting allowable' on each blockface (the continuous frontage along a block, along a single street, between corners at either end; The City of New York, 2017). We then used a data layer representing estimated capacity for street trees along each blockface (provided by NYC Parks) to determine how many additional trees may be planted given the existing ones. We then randomly placed up to that number of points along the respective blockfaces, in accordance with the aforementioned standards.

2.2.4 "Growing" the Canopy

With the areas considered allowable for new tree planting and canopy designated, as well as the points representing potential locations of new street trees, we modeled or "grew" the canopy (illustrated in Figure 2). This entailed buffering the plantable areas and street tree points to represent canopy grown, restricted to the areas considered allowable for canopy. To set a buffer, we calculated the average estimated canopy diameter of street trees and those in landscaped portions of City-owned parkland for the 10 most common species in each, leveraging diameter at breast height from respective datasets (see Treglia et al., 2021a for a more in-depth discussion of these data) and species-specific growth equations (McPherson et al., 2016). The buffer employed was 4.11 m (representing an 8.22 m diameter canopy per tree). The model is not temporal in nature, thus while myriad factors influence canopy size of individual trees, our approach is intended to represent a general average at any given time as young trees are typically planted as larger ones senesce through time. We attributed the canopy "grown" to either new trees that would be associated with plantable areas or to the simulated new street trees. In instances where practical canopy from these sources could overlap (e.g., along boundaries between individual properties and rights of way), we attributed the area of overlap to street trees for accounting purposes, given they are all within the jurisdiction of a single entity (NYC Parks). The spatial data representing canopy "grown" in this step (restricted to exclude spaces considered not allowable for canopy) and those representing plantable area, together comprised the final practical canopy layer (depicted in Figure 2C).

2.3 Characterizing Practical Canopy in New York City

Once the practical canopy layer was developed, we overlaid it with spatial data representing a suite of political, administrative, and jurisdictional datasets to derive descriptive summaries for interpretation, to enable comparison with the distribution of existing canopy, and to support discussion with members of the NYC UFTF. We summarized practical canopy data citywide, and by the following units, in order of decreasing size: boroughs (each representing a single county, and with an elected representative, a Borough President); City Council Districts (each with an elected City Council Member); Community Districts (each with an associated board of community members); and Neighborhood Tabulation Areas (NTAs; a unit used for planning purposes designed to be smaller than City Council Districts, with approximately 15,000 residents within each). Each is relevant to planning and decision-making in NYC, as they align with specific levels of governance, civic engagement, or serve as planning units. We focus our results herein on citywide, borough, and NTA scales, representing the largest and smallest scales, to help highlight overall trends as well as local nuance. NTAs also include aggregated areas that have unique, non-residential uses (e.g., large tracts of land dedicated to parks and airports), which we included in summaries and analysis. Though a set

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of newer NTA boundaries is available, updated after the 2020 decennial census, we used the previously developed layer, created following the 2010 decennial census, to support comparison with previous analyses, such as those of existing canopy (Treglia et al., 2021a, 2021b). A detailed map of boroughs and NTAs is available in Supplementary Material (Supplementary Figure 1).

We also delineated whether practical canopy was associated with street trees, plantable area, or the "growth" around plantable areas, and we characterized the distribution of practical canopy by general jurisdiction (e.g., City properties and rights of way (assumed to be City land), New York State, Federal, or private), and for private property, generalized land uses. Ownership data was generally derived from a parcel dataset available for NYC, MapPLUTO (version 20v6) or agency-specific datasets, described in appendices of Treglia et al. (2021a).

2.4 Canopy Comparisons

We compared the distribution of potential for canopy based on practical canopy by administrative or political unit to breakdowns of existing canopy as of 2017, the most recent time point for which there is a robust, LiDAR-based canopy data layer, using results from Treglia et al. (2021a, 2021b). This comparison allows us to understand what the practical canopy means in terms of opportunities to expand the urban forest in different spaces across the city. At the scale of NTAs, both citywide and by borough, we examined Kendall's τ correlations (Kendall, 1938) to understand the relationship between the percentage of each area covered by canopy as of 2017, and that which would be covered by canopy with the inclusion of practical canopy. This offers insight into whether, in general, adding practical canopy would change the rank order of NTAs in terms of practical canopy (positive correlations would suggest that, in general, practical canopy would not change which areas have the most and least canopy). This analysis was conducted using the cor.test function in R version 4.0.2 (R Core Team, 2020). We also examined whether realizing practical canopy would reduce the disparity in tree canopy by comparing the range in canopy across NTAs by borough based on the existing canopy and the existing plus practical canopy.

We also compared the practical canopy to an estimate of "possible canopy" for NYC (*sensu* Grove et al., 2006; Raciti et al., 2006; considered as a representation of where canopy "biophysically feasible"). For this, we calculated the possible canopy using a comparable methodology to that described by Grove et al. (2006) and Raciti et al. (2006), as the land area that was not existing canopy, water, buildings, roads, or railroads (added as an available, relevant land cover class for this analysis). For this work we leveraged the most recent high resolution landcover data for NYC representing the landscape as of 2017. This comparison allowed us to better understand the differences between the existing typology of potential for new canopy and our proposed typology, 'practical canopy.'

3 Results

3.1 Summaries by Borough and Neighborhood Tabulation Area

The spatial data layer of practical canopy we developed for NYC represents 15,899 hectares (20.31% of the NYC land area) that we estimate could likely be covered by tree canopy from planting and growth of additional trees while accounting for constraints associated with current land use, land cover, and the built environment. The resultant data layer from this work, as well as summaries by borough, City Council District, Community District, and Neighborhood Tabulation Area (2010) is available in a public repository at https://zenodo.org/record/6547492 (Treglia et al., 2022).

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The distribution of practical canopy among the five boroughs of NYC generally followed their rank order by land area, with Queens containing the largest share of all practical canopy in NYC (42.70%) and Manhattan containing the smallest (3.09%) (Table 1). Brooklyn and Staten Island were the only boroughs that did not follow this trend; Brooklyn is the second largest borough but has the third highest practical canopy area, and Staten Island is the third largest borough, but has the second highest practical canopy area. The trends in terms of practical canopy by borough aligns with trends in existing canopy, as of the most recently available canopy dataset for NYC. Staten Island, followed by Queens, had the largest portion of its area identified as practical canopy (27.05% and 24.00%, respectively), with Manhattan having the lowest (8.30%) (Table 1).

Table 1. Summary information of land area, existing canopy, practical canopy, and "possible canopy" (*sensu* Grove et al., 2006; Raciti et al., 2006), by borough of New York City and citywide.

Borough	Land Area (ha)	Practical Canopy (ha)	Existing Canopy 2017 (ha)	Practical Canopy Cover (%)	% of Total Practical Canopy	"Possible Canopy" (ha)	Mean NTA Practical Canopy (%) ± SD	Range of NTA Existing Canopy (%)	Range of NTA Practical + Existing Canopy (%)
Bronx	11,024	1,948	2,733	17.67	12.25	4,294	17.03 ± 9.25	3.06–50.47	14.93–70.81
Brooklyn	17,968	2,591	3,165	14.42	16.3	7,300	14.17 ± 5.48	7.82–27.99	14.90–53.93
Manhattan	5,914	491	1,264	8.3	3.09	1,675	6.83 ± 3.38	2.90–39.51	7.87–59.67
Queens	28,280	6,788	5,344	24	42.7	12,811	26.60 ± 11.71	2.43–35.83	2.95–70.79
Staten Island	15,085	4,080	4,748	27.05	25.66	6,743	30.81 ± 8.54	19.67–48.46	31.81–75.22
Citywide	78,272	15,899	17,254	20.31	100	32,823	18.95 ± 11.56	2.43–50.47	2.95–75.22

Practical canopy within NTAs (Figure 3A) generally reflects the patterns within the respective boroughs, as the rank order for average percent of land area mapped as practical canopy by NTA within each borough was the same as the rank order for percentage of land area mapped as practical canopy by borough as a whole (Table 1). There is substantial variation in the percentage of each unit mapped as practical canopy at this more granular scale; the lowest value for an NTA was 2.74%, in the Clinton area of western Manhattan (MN15) and the highest value was 49.87%, in Cambria Heights, eastern Queens (QN33). In terms of areas with special uses, that representing JFK International and LaGuardia Airports (QN-98) had the lowest percentage of area with practical canopy (0.52%), and Riker's Island (BX-98) had the most (50.47%). The variation tends to be moderated within every borough except for Queens (Table 1).

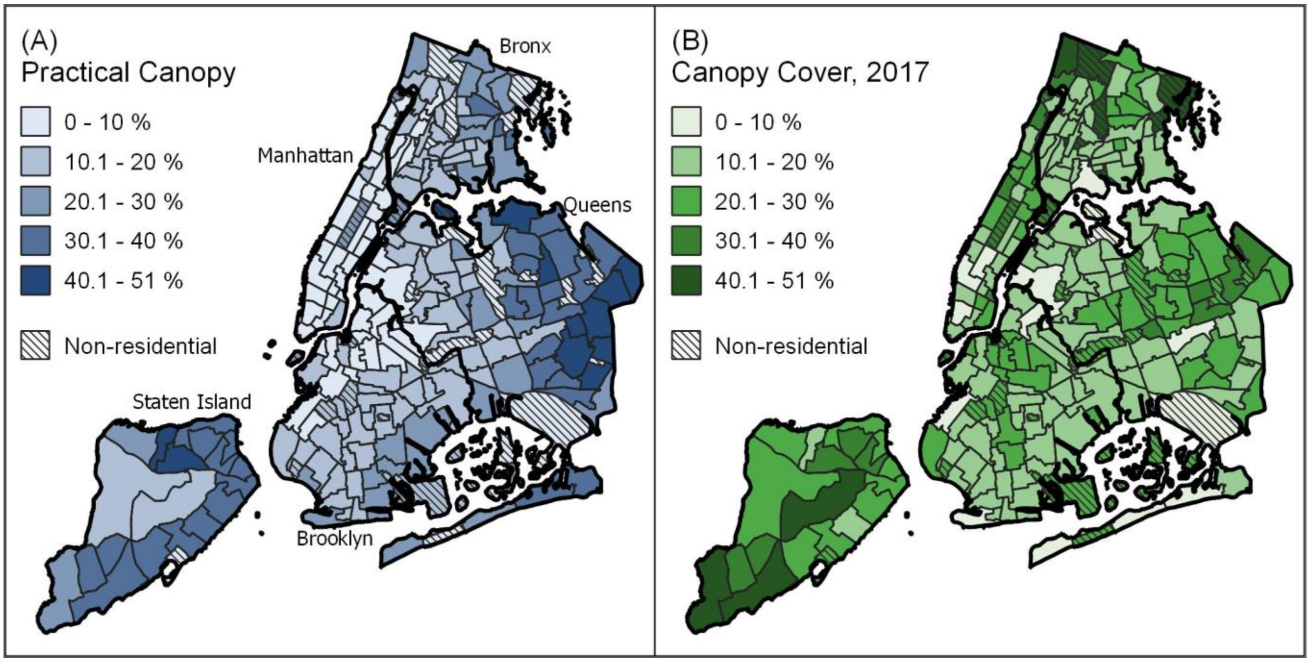

Figure 3. Maps illustrating the practical canopy (A) and existing canopy as of 2017 (B) as percent of land area by Neighborhood Tabulation Area. Thicker borders delineate the borough boundaries (with boroughs labeled on panel A). Borough and Neighborhood Tabulation Area Boundaries are from the City of New York, Department of City Planning. Non-residential areas are generally aggregated by borough in those datasets and as presented here. Summaries of existing canopy cover are from Treglia et al. (2021b).

Citywide, only 6.38% of practical canopy was attributable to street trees, with the remainder associated with spaces considered allowable for planting (34.57%) or the buffered area representing canopy growth from those spaces (59.05%). The Bronx and Queens both have about 6% of their practical canopy attributable to street trees, though Manhattan and Brooklyn have substantially more (14.60% and 10.31%, respectively); Staten Island, has less, only 3.42%. In terms of jurisdiction, the majority of practical canopy mapped (68.78%) was within private property, followed by City land (25.28%; primarily within rights of way, generally associated with canopy grown from plantable area within adjacent properties; see available results files), State (4.14%) and Federal properties (1.80%) (Figure 4A). While this varied by borough, Manhattan was the only one not to have the majority of practical canopy within private property (the majority there, 56.97%, was within the jurisdiction of the City). Further, the large majority of practical canopy mapped on private property was within 1-2 family residential properties, and this was true across all boroughs except for Manhattan, in which the majority of private property practical canopy fell within 3+ family residential properties (Figure 4B). These breakdowns by NTA are available in summary results files.

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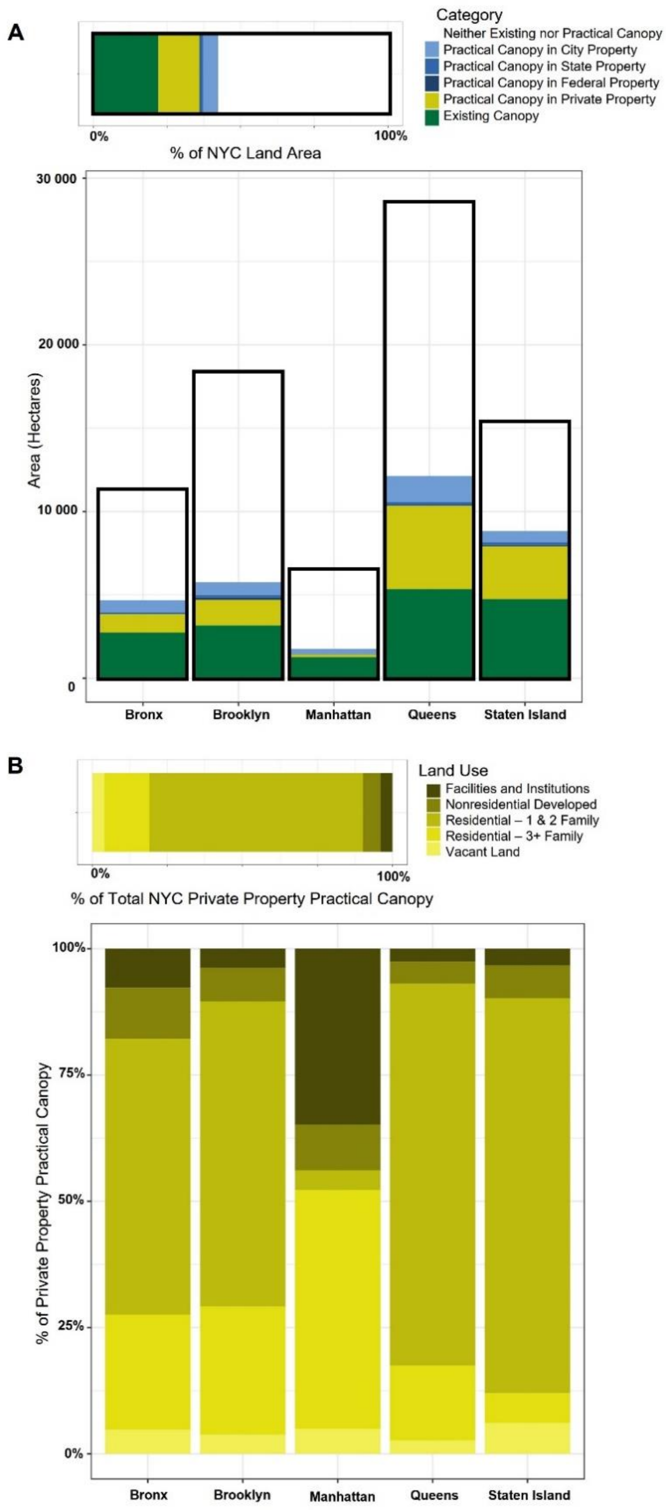

Figure 4. Stacked bar charts showing the distribution of practical canopy by ownership type, as well as existing canopy and land with neither canopy nor mapped practical canopy, both citywide and by borough (A), and the breakdown of practical canopy among different land uses of private property, citywide and by borough (B). For panel A, City Property includes rights of way, generally within the jurisdiction of the City of New York; when State or Federal practical canopy is not discernable, it represented a small very small portion, if any, of the practical canopy. For panel B, land uses are aggregated from parcel data for NYC (see Supplementary Material).

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3.2 Practical Canopy Compared to Existing (2017) Canopy and "Possible Canopy"

The 15,899 ha of practical canopy mapped citywide represents nearly the same total area of tree canopy in NYC as of 2017, 17,254 ha (Treglia et al., 2021a), indicating the potential to nearly double tree canopy at this scale if all practical canopy were realized and existing canopy cover was maintained (achieving 42.35% canopy cover total). Given the variation in borough-level canopy and practical canopy (Table 1) the largest relative increases would be the greatest in Queens (127.04%), more than doubling its canopy, and the smallest would be in Manhattan (38.84%), with the potential relative increases in other boroughs ranging 71.27% - 85.93%.

Citywide and across all five boroughs, we found significant positive correlations between the practical canopy and practical plus existing canopy within NTAs (Figure 5). This indicates that, in general, the rank-order of the NTAs in terms of canopy would not change if all practical canopy mapped in this analysis were realized. Further, in all boroughs, the range of canopy cover across the NTAs would increase. Thus, while all NTAs would see at least some increase in canopy cover, realizing practical canopy would lead to an increase in the disparity between areas with the most and least canopy; the ranges in canopy across NTAs would increase in all boroughs and citywide (Table 1).

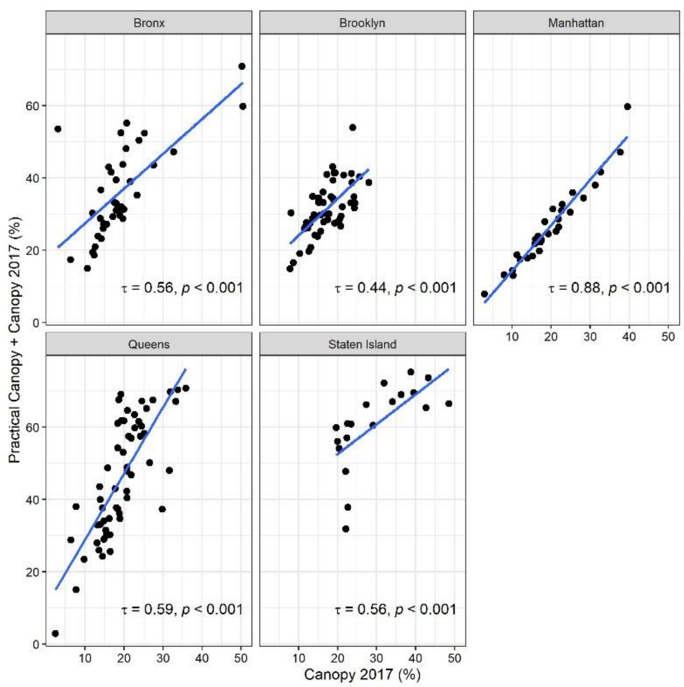

Figure 5. Scatterplots, by borough, showing existing canopy (as of 2017) and the combination of practical and existing canopy, both as percentages of land area for each Neighborhood Tabulation Area. τ represents Kendall's τ correlation coefficient, and p represents the respective p-value.

Our estimate of "possible canopy" (*sensu* Grove et al., 2006; Raciti et al., 2006) (32,823 ha) was more than double the area of practical canopy. The "possible canopy," relative to practical canopy, was highest in Manhattan and Brooklyn (3.41 and 2.82 times higher, respectively), and lowest in

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Staten Island (1.65 times higher). "Possible canopy" covered 41.93% of the NYC landscape, and if added to existing canopy would suggest opportunity for a total of 63.98% canopy cover citywide.

4 Discussion

Our estimate of practical canopy suggests the existing NYC landscape could likely support 15,899 ha of additional tree canopy. If all practical canopy were realized and the existing canopy is maintained, the canopy cover in NYC would nearly double, to 42.35% of the land area. The methodology we developed relies on making explicit assumptions of where trees could be planted, informed by local context and data, and thus it enables deeper conversations or iterative analysis depending on the needs of those using the information. Comparing existing canopy cover, "possible canopy," and practical canopy additionally provides a more complete picture of urban forest possibilities in a way that enables discussion of what may be required to address inequities in the NYC urban forest. Notably, the existing urban forest in NYC should not be taken for granted, as it is susceptible to loss from various challenges, requiring ongoing protection and stewardship (Treglia et al., 2021a). Protection and stewardship would also be required for newly planted trees to achieve the canopy simulated in the practical canopy analysis. It is imperative that future planning efforts take these dynamics into account. Ultimately, by promoting deeper conversation and a nuanced understanding of the landscape, the practical canopy analysis facilitates a framework for a 'priority' canopy, which can then be acted upon. Our NYC practical canopy analysis grounded discussions around what a feasible but ambitious goal could be in the current urban landscape. It not only informed the 30% canopy cover by 2035 goal put forth in the *NYC Urban Forest Agenda*, but also has made clear that to achieve a more just urban forest, it will likely be necessary to create new spaces for planting, beyond what exists in the current landscape. Throughout this process, conversations have been in line with what is required to set forth a virtuous cycle (Morrison, 2016) where technical information and analysis, such as practical canopy mapping, are tools to create buy-in, in iteratively larger circles of stakeholders.

In mapping practical canopy for NYC, we developed explicit assumptions related to where the landscape could likely support planting of new trees and addition of canopy, through conversation with local experts in the urban forest. This was based on best available data, almost all of which was publicly available, that captured myriad aspects of land cover, land use, and the built environment. The wealth of data available enabled robust discussions about the assumptions and enabled a common, shared understanding of the limits of this analysis. We examined data together and noted examples where the data simply could not capture real limits in where the urban forest could be expanded – for example, some areas in City-owned parkland that are not well suited to expansion of the urban forest as active recreation fields are not always captured in the data, as is the case with the infield of the Kissena Velodrome in Queens. Further, while that is an example of over-estimation of practical canopy, we may have under-estimated practical canopy in cases as well, with assumptions of limited opportunity for planting on cemeteries and within airport boundaries. Thus, more robust data, and even further refined assumptions could improve this analysis. Further, experimentation with different assumptions could enable a sensitivity analysis to understand their impact more fully.

We see the iterative process of considering data and assumptions together as a refinement of the three P's ("possible," "potential," and "preferable" canopy; Grove et al., 2006; Raciti et al., 2006) as the general categories of each P, "biophysical," "economic," and "preferable", are not truly distinct. Instead, they inform each other and are dependent on the people making decisions, generally based on the data available. Their application then demands a step that is "practical," working explicitly to ground conversations and priorities without being prescriptive. Our effort to explicitly document the data and assumptions can enable researchers and practitioners to refine this work based on new information or different objectives. For example, while cemeteries were considered not suitable for tree planting in our analysis, we recognize there is variation in how cemeteries are managed. The Green-Wood cemetery, as a case in point, is an arboricultural leader, qualified as a Level III Arboretum (Treglia et al., 2021a). Thus, additional opportunities for new canopy can be explicitly incorporated with refined or targeted analyses and assumptions. Functionally, the practical canopy is a spatial model that does not necessarily incorporate local perspectives, all constraints at play, or the potential to fundamentally change the landscape to create new canopy or planting opportunities (e.g., un-paving land). However, it can ultimately inform where fundamental changes to the landscape may be needed to achieve expansion of the urban forest.

The comparisons between the practical canopy and both the existing and "possible" canopies for NYC elucidate how context dependent understanding of opportunities for urban forest expansion can be. We expected the "possible canopy" to be greater than practical canopy because the former focuses only on particular biophysical assumptions of where new canopy can go, without consideration for where trees from which that canopy would grow can be planted or what the actual land uses are (e.g., if land is used for active recreation). In early work, we explored applying the "possible canopy" methodology of Grove et al. (2006) for NYC. We recognized its utility in starting conversations, and we began to better understand its limits. It ultimately inspired development of the idea of practical canopy, particularly given the wealth of data available for NYC that enabled a more realistic model that can account for specific constraints and opportunities for the urban forest. For example, while "possible canopy" does not allow canopy over any buildings or roadways, we were able to incorporate potential for canopy over short buildings and surface roads into practical canopy.

In exploring the relationships between practical canopy and existing canopy, we observed that while all areas of the city had some practical canopy, many areas with little existing canopy also had little practical canopy. Examples include in midtown Manhattan and, to a more moderate degree, the South Bronx (Figure 3). While one might expect that places with low canopy would have more opportunity for new canopy because they have not been paid attention to for urban greening, our result shows that the existing landscapes, driven by various factors that shaped development history, have real constraints in terms of expanding the urban forest, as these areas have urban forms that are largely incompatible with broad greening efforts. Places with low canopy cover that have generally not had green space prioritized have often been paved over for other uses (Gould and Lewis, 2017) and are not simply "low-hanging fruit" for expanding the urban forest. We see this is indeed a general trend, as realizing practical canopy cannot counter the disparities in existing canopy across the city, though there are exceptions (see Figure 5).

Our results show that reducing disparities in tree canopy across NYC will require meaningful changes in the landscape that enable more planting of trees where there is little canopy. In general, urban forest goals are often established at a citywide level to improve access to benefits of trees and their canopy, and sometimes vegetation more generally, as in the case of efforts to mitigate urban heat challenges, particularly given warming temperatures associated with climate change (Eisenman et al., 2021). However, consideration of more granular spatial units is often needed to be relevant for the local impacts of challenges such as the urban heat island effect: in NYC, Johnson et al. (2020) identified a 32% vegetative cover threshold within a 12.6 ha area (approximately equivalent to a Manhattan block) before temperatures are cooled by vegetation, and in Madison, WI, USA, Ziter et al. (2019) suggested that 40% canopy cover in a 25 ha area is required before the cooling effects of increased vegetation are felt. When we consider our practical canopy results, neither the hottest areas (see Johnson et al., 2020) nor the areas with the most heat-vulnerable communities (mapped by the

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NYC Department of Health and Mental Hygiene) are among those with the most practical canopy (with a notable exception of Jamaica, Queens; Figure 3) or those that would see their circumstances substantially change in terms of canopy (Figure 6). This result may partially reflect that the driving force in the urban heat island effect is the differential rates of energy storage and release by different substrates, of which impervious surfaces (buildings and paved surfaces) store and release the most heat (Ward and Grimmond, 2017). Thus, the hottest areas (albeit not always the most heat vulnerable ones) may inherently be some of those with the least practical canopy given the high rates of impervious surfaces. Additionally, the findings of Johnson et al. (2020) and Ziter et al. (2019) suggest some of these interventions have to be considered at a scale as small as individual blocks, since at larger scales, cooling effects of trees may not be felt from one edge of a unit to another. While increasing access to the urban forest and its benefits is important through lenses of equity, public health, and general climate resilience, it is important that communities affected are authentically engaged, with opportunities for their visions to be elevated to support their self-determination for a more just end result (Campbell et al., 2022).

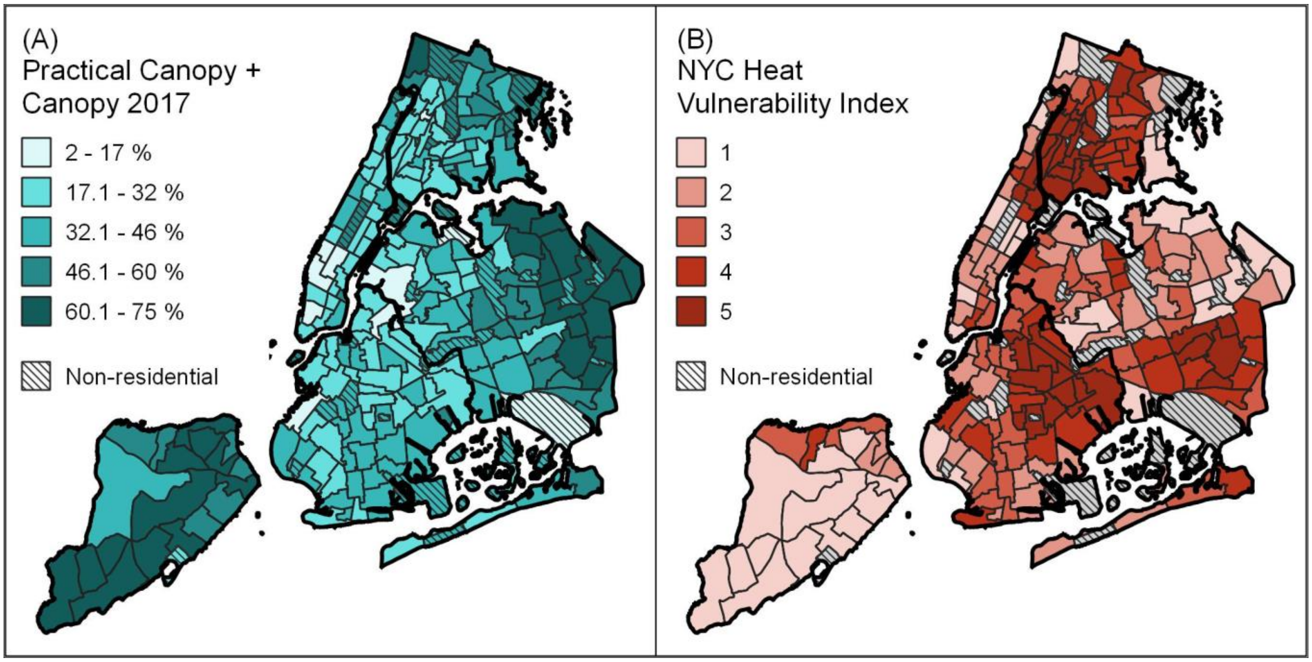

Figure 6. Maps illustrating what canopy cover (%) would be if all practical canopy mapped were realized, assuming maintenance of existing canopy as of 2017 (A), and the NYC Heat Vulnerability Index (2018 version), by Neighborhood Tabulation Area (B). Borough and Neighborhood Tabulation Area Boundaries are from the City of New York, Department of City Planning. Non-residential areas are generally aggregated by borough in those datasets and as presented here. Data on existing canopy used in panel A are from Treglia et al. (2021a, 2021b); the NYC Heat Vulnerability Index is available from the NYC Department of Health and Mental Hygiene at https://a816-dohbesp.nyc.gov/IndicatorPublic/VisualizationData.aspx?id=2411,719b87,107,Map,Score,201.

Three examples of means by which the landscape can be changed to accommodate expansion of the urban forest are: through broad changes in zoning regulations; rezoning specific neighborhoods; and redesigning streetscapes, within which street trees are generally planted. For example, in 2008, the City Planning Commission in NYC created a requirement in the zoning resolution that in almost all cases, new buildings and large alterations city-wide have to either plant or protect a street tree for every 7.62 m of frontage on the building (Zoning Resolution of the City of New York, 2011). Further, local areas can have more regulations or enabling conditions that support protection and expansion of the urban forest as part of zoning processes. For example, rezoning can result in future development (or redevelopment) that creates more opportunities for tree planting and canopy growth, and special purpose zoning districts can be established with more specific urban forestry requirements (e.g., as with the Special Natural Area District; Treglia et al., 2021). Finally, the COVID-19 pandemic and a citywide commitment to decrease dependence on fossil fuels have created space for conversations on re-envisioning the right-of-way (Freudenberg et al., 2021). Streetscapes can be designed to prioritize vegetation, permeable surfaces, often in concert with other sustainable and livability improvements for pedestrians and cycling. This can ultimately support de-pavement and tree planting, and even daylighting of below-ground streams (that were once aboveground) with riparian vegetation buffers (Freudenberg et al., 2021). Deciding which strategy makes sense where, and how to prioritize expansion of the urban forest requires coordination with those who will be affected by such decisions and landscape changes. Policy interventions to drive landscape change should be developed with local participation and hand-in-hand with other policies that prevent consequences such as green gentrification, if the goal is to expand urban forest benefits to those who stand to benefit the most (Gould and Lewis, 2012; Schell et al., 2020; Campbell et al., 2022; García-Lamarca et al., 2022).

In general, mapping practical canopy can serve as a foundation for locally grounded conversations around priority canopy – where canopy is most desired and needed for its benefits, regardless of the existing constraints. This can build on and perhaps incorporate existing prioritization approaches that strive to represent various perspectives from across a city (e.g., Locke et al., 2010, 2013), while centering on more local perspectives. Stakeholders and decision makers can inspect results in dialogue within the context of other relevant initiatives, the policy landscape, and priorities of the local communities. As aforementioned, in NYC specifically we generally observe high practical canopy in NTAs with high existing canopy. Thus, practical canopy and existing canopy can be considered together, along with other data, to develop generalized solutions that can be customized for local needs and desires. Specifically, high practical canopy but low existing canopy in an area can suggest the need to leverage available planting spaces; low practical and low existing canopy may suggest a need to re-envision the local landscape, and areas with high existing canopy, in general, may require tree preservation and stewardship efforts, and it is critical that these be considered more broadly in planning for the resource. Practical and existing canopy each reflect some dimensions of land use and social or natural histories that can be made more explicit, and preferences and needs for the future can be developed from there, by or with local communities.

Understanding dimensions of existing and practical canopy can also have implications for broader planning efforts, particularly when considered with jurisdictional and land use data. Based on our analysis in NYC, from a citywide perspective, it may be critical to prioritize engagement with private property owners, particularly those that own 1-2 family residential properties (Figure 4B), given the substantial practical canopy. Yet, geographically targeted analyses, such as in heat vulnerable areas with limited practical canopy, may guide local efforts involving the community and government agencies to ensure a robust urban forest in the public space (e.g., street trees) or to redesign the streetscape or rezone an area to create opportunities for additional tree plantings. In such local efforts, however, it is critical to ensure local stakeholders such as residents and community-based organizations are authentically engaged. Through dialogue with local communities (tenants,

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homeowners, workers, political and economic actors, identity affiliations, and others), at the scale of participation that is appropriate (Arnstein, 1969; Campbell et al., 2021), valuable additional information for the priority canopy framework can be included. The landscape of politics often defines this information, for example, to balance sometimes competing priorities and understand tradeoffs (e.g., increasing building height and density to promote an increase in housing density). The urgency of climate change also requires different information to be incorporated into urban forest decision making, such that heat- and flood- tolerant tree species need to be considered at the same time as the mitigation effects of the urban forest. As urban forest goals are implemented, these complexities can be layered on top of the existing and practical canopies to create a priority canopy.

In NYC, our development of the practical canopy analysis was spurred by conversations with other stakeholders in the NYC UFTF, in part, as a means of informing the canopy goal in *The NYC Urban Forest Agenda* (NYC Urban Forest Task Force, 2021). The NYC UFTF was composed of approximately 50 organizations that worked to collaboratively develop the *NYC Urban Forest Agenda* between 2019 and 2021. During this time, the NYC UFTF agreed they needed, among other things, a citywide goal that would support planning, guide policy initiatives, and to spark individual and collective action. Canopy was agreed upon as preferred metric for goal setting for several reasons: it can be measured and compared through using periodic LiDAR-based data (when available); its change over time reflects a collection of actions or events relative to the resource (including planting, protection or lack thereof, maintenance, stochastic events); its extent may correlate to service provisioning; and it can be understood and compared at different scales relevant to policy-making and interest of local communities. Once canopy was selected for the goal metric, the NYC UFTF leadership wanted a grounding in the potential for additional canopy, which led to our development of practical canopy. It was critical that the goal be set within the context of potential (even if ambitious) resources such as funds and availability of trees to plant, and guiding principles or values (e.g., increasing equity of the urban forest, particularly through lenses of health, and climate resilience, per the *NYC Urban Forest Agenda*). Further, it was desired for the goal to be aspirational but achievable, and simple such that it could be digestible and galvanizing, in ways that could inspire and require policy improvements, increased investments, and an expanded urban forest workforce, while having potential to improve environmental quality and climate resilience. It was also important that the goal be time-bound, such that it could spur both immediate and sustained action, while allowing for sufficient time to measure progress. Achieving a more equitable distribution, in addition to higher citywide canopy cover, was a key part of the conversation. Thus, the development and exploration of practical canopy enabled such discussions, resulting in a citywide canopy goal of 30% by 2035.

Since the release of the *NYC Urban Forest Agenda* in June 2021, myriad stakeholders have taken on the goal to varying degrees. The applicability of the goal across geographic scales and potential to touch down in local communities that can see benefits may enable this to be the start of a virtuous cycle (Morrison, 2016). While mapping practical canopy was highly technical work, it ultimately supported buy-in for a canopy goal and allowed those engaged in the process to see the opportunity, and potential for broad engagement by others, in expanding the urban forest. The opportunity identified, to at least some degree throughout the city and across jurisdictions, to increase canopy was galvanizing. Perhaps the same quantitative goal could have been set without this consultative process of mapping practical canopy (or with a simpler analysis), but the effort created buy-in via participation and discussion. Further, the practical canopy data layer can be a tool for conversation and to inform ways in which the 30% canopy by 2035 goal can be achieved. As the *NYC Urban Forest Agenda* was released, the NYC Urban Forest Task Force launched the Forest For All NYC Coalition, which includes approximately 50 organizations and is working to advance the canopy

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goal, among other actions detailed in the *Agenda* to support the NYC urban forest. The Coalition has successfully advocated adoption of the goal by the Chair of the NYC Council Committee on Parks and Recreation. Tree planting goals are still part of the conversation in NYC, with a "Million More Trees" campaign initiated by the five Borough Presidents. However, the Coalition has effectively advocated the campaign incorporate the canopy goal, potentially strengthening both initiatives simultaneously. Ultimately, a virtuous cycle for the NYC urban forest may be in its early stages. If so, it is likely supported by technical information grounded in the landscape context, in the form of the practical canopy analysis, that can facilitate stakeholder engagement and planning for expansion of the resource with consideration of local priorities.

5 Data Availability Statement

Data used in the analyses are detailed in a combination of the methods sections and the supplementary materials. In most cases, data used in analyses are publicly available and links to them are provided, though some data used are not publicly available and were used specifically for this work under data sharing agreements. Results files associated with this work, including the practical canopy data layer and summaries by administrative, political, and planning units are available on Zenodo at https://zenodo.org/record/6547492.

6 Author Contributions

EM and MT developed the initial concepts of practical and priority canopy as described in the paper, led meetings that resulted in input and feedback from partners, contributed to writing the first draft of the manuscript, and supervised the overall work. KL and MT developed and applied the novel methodology for mapping practical canopy and MT led the calculation of possible canopy. NP led the writing of the first draft of the manuscript and led refinement of the framing for practical and priority canopy as described in the manuscript. AVS and MT conducted post-processing of the practical canopy data layer to summarize results by different geographic and jurisdictional units. AVS, KL, MT, and NP developed figures for the manuscript. All authors contributed to revision of the manuscript, and read and approved of this submission.

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Supplementary Material

Detailed methods and descriptions of data underlying the analyses, as well as a detailed map of boroughs and Neighborhood Tabulation Areas discussed in this work are available in the following supplementary material. Further, supplementary results files including the practical canopy data layer that resulted from this work and summaries by units specific to New York City are available on Zenodo at https://zenodo.org/record/6547492.

Supplementary Material

Supplementary Methods

This section describes the data and methods used to develop an analysis of 'practical canopy' in New York City, New York, USA, described in the associated manuscript.

Development of the Baselayer

Supplementary Table 1 shows the suite of data layers used in development of the baselayer (used for mapping practical canopy for non-street trees) and as applicable, where they may be accessed. These were accessed during November 2020-March 2021. Almost all of these datasets are publicly available (per links in the table), though others were shared for use in this work as noted. The general overall workflow for creating the baselayer was to:

1. Compile datasets to be used (Supplementary Table 1) and identify what layers or types of features to include (e.g., Supplementary Table 2).
2. Set allowability rules for planting and canopy (Supplementary Table 3).
3. Set rules for how overlapping features would be handled or prioritized (Supplementary Table 3).
4. Merge the features into a single data layer

Supplementary Table 1. General datasets used in mapping of practical canopy. Datasets associated with NYC Parks (the New York City Department of Parks and Recreation) include coverage for land within that agency's jurisdiction.

Dataset	Source (URL or explanation)
NYC Planimetric Data (based on 2014 aerial imagery)	https://data.cityofnewyork.us/Transportation/NYC-Planimetrics/wt4d-p43d
NYC Land Cover Raster Data (2017), 6in Resolution	https://data.cityofnewyork.us/Environment/Land-Cover-Raster-Data-2017-6in-Resolution/he6d-2qns
NYC Tree Canopy Change (2010 – 2017)	https://data.cityofnewyork.us/Environment/Tree-Canopy-Change-2010-2017-/by9k-vhck
LION Single Line Street Base Map (version 20c)	https://www1.nyc.gov/site/planning/data-maps/open-data/dwn-lion.page
Building Footprints (from August 2020)	https://data.cityofnewyork.us/Housing-Development/Building-Footprints/nqwf-w8eh
Ecological Covertype Map (Level 2)	Shared by the Natural Areas Conservancy under data sharing agreement. See the following reference for details of this dataset: O'Neil-Dunne, J., MacFaden, S. W., Forgione, H., and Lu, J. W. (2014). Urban Ecological Land-cover Mapping for New York City. Natural Areas Conservancy.
Dominant Type Data Layer (NYC Parks)	Shared by NYC Parks under a data sharing agreement
Beaches on City Parkland (NYC Parks)	https://data.cityofnewyork.us/dataset/Beaches/ijwa-mn2v
Synthetic Turf Fields (NYC Parks)	https://data.cityofnewyork.us/Recreation/Synthetic-Turf-Fields/weh8-3ujf
Landfills (NYC Parks)	https://data.cityofnewyork.us/City-Government/Landfills/6gvx-hydd
Golf Courses (NYC Parks)	https://data.cityofnewyork.us/dataset/Golf-Courses/dc95-rgxd
Dog Runs (NYC Parks)	https://data.cityofnewyork.us/Recreation/NYC-Parks-Dog-Runs/8nac-uner

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Concession Areas on City Parkland (NYC Parks)	https://data.cityofnewyork.us/City-Government/Parks-Concessions/53m8-jdtg
GreenThumb Community Gardens (NYC Parks)	https://data.cityofnewyork.us/dataset/GreenThumb-Garden-Info/p78i-pat6
Athletic Facilities (NYC Parks)	https://data.cityofnewyork.us/dataset/Athletic-Facilities/qnem-b8re
NYC Parcel Dataset, MapPLUTO versión 20v6	https://www1.nyc.gov/site/planning/data-maps/open-data.page#pluto

Most of the data used were from the NYC Planimetric dataset which has a suite of distinct layers within it. Those used in the analysis are highlighted in Supplementary Table 2 with any specific notes as to how they were used. The rules in Supplementary Table 2 for the “PARK” layer were also applied for the NYC Parks Athletic Facilities layer. Further, some layers within the NYC Planimetric dataset were not used, thus those are not included in the table.

Given the NYC Planimetric dataset was developed through digitization of aerial imagery from 2014, we supplemented associated layers with more recent datasets when possible. In particular, we spatially joined road features in the NYC Planimetric data to a line dataset that is regularly updated by the City, “LION,” as detailed below, with input from the Natural Areas Conservancy (metadata and data dictionary for the LION dataset used is available at https://www1.nyc.gov/assets/planning/download/pdf/data-maps/open-data/lion_metadata.pdf?r=20c).

1. NYC Planimetric roadbeds with subtype “ROADBED” were used as the base to which LION roads data was joined to. (Roadbeds with subtypes Shoulders, Driveways, and Intersections were not used in this join analysis.) Roadbeds within airports were also manually removed.
2. LION features of interest were identified using the attribute RW_TYPE:
    a. RW_TYPE NOT IN ('12', '14') And FeatureTyp NOT IN ('1', '2', '3', '5', '7', '9', '8','F') And SegmentTyp NOT IN ('F', 'T', 'S', 'G')
3. Unnecessary fields were deleted.
4. Spatial Join-Largest Overlap was used to join LION features to roadbed features.
5. From the joined roadbed data, the following features were extracted using the RW_TYPE field: Streets (including streets, alleys, driveways); highways (including highways, ramps, U-turns); and bridges
6. Of the remaining joined roadbed data, most were identified as "Path/Trail" and included bikeways, pedestrian paths, and driveways with parking. Step Streets (n = 6) were also added to Path/Trail roadbeds.
7. Of planimetric roadbeds that did not spatially intersect (i.e., they were not joined to) any LION lines, there were several visually identifiable clusters of paths in housing complexes, campuses, and cemeteries.
    a. Streets along the eastern edge of the study area (boundary between Queens County and Nassau County) did not join to LION; these were manually assigned to FeatureName “lion_street” and RW_TYPE = 1. (Note – for consistency with the Lion data, entering a 1 required a space before it, as it is a non-numeric (string type) field.)
8. Of LION lines that did not intersect with roadbed features, the longest, most prominent features represented bikeways and paths along riverside parks and did not seem to overlap with any other layer except the planimetric Parks - Park Boundary polygons. This may be a

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limit of the data driven by different time periods they represent. There were also features overlapping with Sidewalk Interior layer, suggesting that this layer should be ranked lower than at least the Sidewalk layer.

9. Tunnels and features containing the keyword "%UNDERPASS%" were excluded from the analysis.

Supplementary Table 2. Specific data layers from the NYC Planimetric dataset (available as a .gdb file with multiple layers) used in analysis, with notes as needed to specify how they were used. The layer names and subtypes are described by the NYC Department of Information Technology and Telecommunications at: https://github.com/CityOfNewYork/nyc-planimetrics/blob/master/Capture_Rules.md.

Layer name	Subtype(s)	Feature Type as Considered in Analysis	Notes
BOARDWALK	N/A	plani_boardwalk	
HYDRO_STRUCTURE	JETTY	jetty	
HYDRO_STRUCTURE	PIER	pier	
HYDROGRAPHY	N/A	hydrography	Piers and jetties were erased from this layer to avoid redundancy.
MEDIAN	Median_Painted	median_painted	
MEDIAN	Median_Curb	median_curb	
MEDIAN	Median_Rail	median_rail	
MEDIAN	Median_Fenced	median_fenced	
MEDIAN	Median_Grass	median_grass	
MEDIAN	Median_Barrier	median_barrier	
OPEN_SPACE_NO_PARK	Cemetery outline	cemetery_outline	
OPEN_SPACE_NO_PARK	Recreational area (not NYC designated parks)	recarea_nopark	
OPEN_SPACE_NO_PARK	Vacant area containing no structures	vacant	
PARK	Baseball/Softball field; Basketball Court; Handball Court; Multipurpose Court; Tennis Court; Volleyball Court; Soccer Field; Pools; Track	athleticfacility_can	Athletic facilities that allow canopy to overlap. Each feature was buffered by 100 ft (30.48 m) after visual inspection and consultation with partners, as the boundaries in the data under-represented the functional extent of the athletic facility.
PARK	Football Field; Skating Rink	athleticfacility_nocan	Athletic facilities that do not allow canopy to overlap. Each feature was buffered by 100 ft (30.48 m) after visual inspection and consultation with partners, as the boundaries in the data under-represented the functional extent of the athletic facility.
PARKING_LOT	N/A	parking_lot	
PLAZA	N/A	plaza	
RAILROAD_STRUCTURE	Subway/Train Station; Elevated Subway/Train Station; Transit Entrance	railroad_nocan	Railroad features that do not allow canopy to overlap.
RAILROAD_STRUCTURE	Ventilation Grate	rr_ventgrate	
RAILROAD_STRUCTURE	Emergency Exit	rr_emergencyexit	

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Layer name	Subtype(s)	Feature Type as Considered in Analysis	Notes
ROADBED	Roadbed	lion_highway; lion_bridge; lion_pathtrail; lion_street; roadbed_other	Roadbeds were joined to LION roads data and classified (see roads analysis methodology). Any remaining roadbeds that could not be joined to LION data were classified as "roadbed_other".
ROADBED	Intersection	intersection	
ROADBED	Driveway	driveway	
ROADBED	Shoulder	shoulder	
SIDEWALK	Interior sidewalk	sidewalk_interior	
SIDEWALK	Right-of-Way Sidewalk	sidewalk_row	Specifically not considered allowable for planting in the baselayer but used to simulate street tree practical canopy.
TRANSPORT_STRUCTURE	N/A	N/A	Subtypes Tunnel, Overpass, Rail Bridge, and Railroad viaduct were not used. Railroad features were accounted for using the land cover raster layer.
TRANSPORT_STRUCTURE	Bridge	plani_bridge	
TRANSPORT_STRUCTURE	Pedestrian/Bike Bridge	plani_pedestbridge	

As noted in the manuscript, natural areas were not considered allowable for planting or canopy in this analysis. For land within the jurisdiction of NYC Parks, natural areas were delineated as areas considered "Natural" in the Dominant Type dataset; for all other parts of the city, natural areas were delineated as those with the following habitat types according to the Ecological Covertype Map dataset: Forested Wetland, Freshwater Aquatic Vegetation, Freshwater Wetland, Inland Water, Maritime Forest, Off-Shore Water, Saltwater Aquatic Vegetation, Tidal Wetland, Upland Forest, and Upland Grass/Shrub. Airports were also not considered allowable for planting and canopy; the boundaries for those in NYC (JFK International and LaGuardia) were extracted from MapPLUTO, and manually adjusted to encompass areas that were understood by us and partners to have restrictions based on proximity to the airports and alignment with runways.

We delineated buildings as being allowable for additional canopy (short buildings) or not (tall buildings) based on exploratory analysis of data representing existing (2017) canopy and the building footprints. We overlaid data for existing canopy with building footprints and calculated the percent canopy cover for each building and explored the data in bins of 10% canopy cover (0-10%, 10-20%, etc.), ultimately focusing on those with 10-20% as representative for purposes of setting the height threshold for tall buildings. While the building footprint and canopy datasets are overall considered highly accurate, less canopy can include instances of inaccuracies in the data, and higher canopy cover over buildings tends to be over building footprints that are smaller and with less complex, more square shapes. Of the buildings with 10-20% canopy cover, we calculated the 90th percentile of height for those that had height recorded as non-zero as the threshold for canopy allowability (34.62 ft) to determine the threshold for short vs tall buildings in this work. Some taller buildings with potential for canopy may have been excluded, but these are rare, and based on our inspection of the data, are sometimes the case with complex topography (e.g., a building on the lower portion of a steep topography change).

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Supplementary Table 3. Specific types of features from the various datasets incorporated into the baselayer for mapping practical canopy. Feature Type indicates the layer name that was used in analysis; Source indicates the source dataset, associated with Table 1; Planting Allowable and Canopy Allowable indicate whether the respective spaces were considered allowable for planting and canopy in the spatial model; Priority Rank delineates what order these were considered in in cases of overlap with other layers when creating the baselayer (lower values [higher rank] were given higher priority).

Feature Type	Source	Planting Allowable	Canopy Allowable	Priority Rank
canopy_exist	NYC Canopy Change Data	0	0	100
airport	MapPLUTO	0	0	110
railroad	NYC Landcover	0	0	200
plani_pedestbridge	NYC Planimetricc	0	0	210
plani_bridge	NYC Planimetric	0	0	211
lion_bridge	LION/NYC Planimetric	0	0	212
lion_highway	LION/NYC Planimetric	0	0	213
shoulder	LION/NYC Planimetric	0	0	214
hydrography	LION/NYC Planimetric	0	1	220
dpr_natural	Dominant Type	0	0	222
beach	Beaches	0	0	250
jetty	NYC Planimetric	0	0	251
bldg_lg	Building Footprints (>35 ft tall)	0	0	310
plaza	NYC Planimetric	1	1	315
median_painted	NYC Planimetric	0	0	330
median_curb	NYC Planimetric	1	1	331
median_rail	NYC Planimetric	0	0	332
median_fence	NYC Planimetric	0	0	333
median_grass	NYC Planimetric	1	1	334
median_barrier	NYC Planimetric	0	1	335
bldg_small	Building Footprints (≤ 35 ft tall)	0	1	350
intersection	NYC Planimetric	0	1	351
driveway	NYC Planimetric	0	1	352
lion_street	LION/NYC Planimetric	0	1	353
parking_lot	NYC Planimetric	1	1	360
cemetery_roadbed	NYC Planimetric	0	1	440
landfill_roadbed	NYC Planimetric	0	1	441

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Feature Type	Source	Planting Allowable	Canopy Allowable	Priority Rank
community_garden	GreenThumb Community Gardens	0	0	450
landfill	Landfills	0	1	455
railroad_nocan	NYC Planimetric	0	0	460
rr_ventgrate	NYC Planimetric	0	1	461
rr_emergencyexit	NYC Planimetric	0	1	462
sidewalk_interior	NYC Planimetric	0	1	470
sidewalk_row	NYC Planimetric	1	1	471
boardwalk	NYC Planimetric	0	1	472
lion_pathtrail	LION/NYC Planimetric	0	1	473
roadbed_other	NYC Planimetric	0	1	490
golfcourse	Golf Courses	0	1	500
concessionarea_no	Concession Areas	0	0	501
cemetery_outline	NYC Planimetric	0	1	502
athleticfacility_nocan	Athletic Facilities/NYC Planimetric	0	0	503
athleticfacility_can	Athletic Facilities/NYC Planimetric	0	1	504
dogrun	Dog Runs	0	1	505
syntheticturf	Synthetic Turf	0	1	506
dpr_dev	Dominant Type	1	1	590
recarea_nopark	NYC Planimetric	0	0	591
vacant	NYC Planimetric	1	1	592
pier	NYC Planimetric	1	1	595

The baselayer was created based on the aforementioned data layers and with the rules set in Supplementary Table 3 in ArcGIS Pro version 2.8, with some inspection and processing of data done in QGIS and PostGIS. Any raster data used (e.g., the railroad data from the land cover raster) were vectorized for this step.

Mapping Practical Canopy

For areas in the mashup not considered as natural areas or right-of-way sidewalks, we overlaid permeable, non-canopy classes of the land cover raster dataset (grass/shrubs and bare soil) as polygons. Within areas considered allowable for planting per Supplementary Table 3, only those spaces that had permeable land cover and were at least 25 ft^2 were considered allowable for planting in subsequent steps. This ensures enough space for at least a small tree bed, though larger spaces are often preferable. Sidewalks in rights of way were considered separately from the rest of the landscape, as tree beds may be cut into pavement. Thus, the rules for these spaces were followed as detailed in the manuscript itself.

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We buffered the areas mapped as allowable for planting by a radius of 13.5 feet to represent canopy growth from those spaces, as described in the manuscript, and then clipped that to exclude areas not considered allowable for additional canopy on the landscape. The same buffer and clipping was applied to points representing simulated new street trees (placed on the landscape per the description given in the manuscript).

There were cases where canopy "grown" from areas considered allowable for planting would overlap canopy grown from simulated street trees. In such cases, to avoid double counting of practical canopy area, that canopy overlap was combined into a single polygon, and was associated with practical canopy from the simulated new street tree points. The results of this work – the final areas considered as allowable for planting plus the canopy "grown" and then clipped to only include areas allowable for canopy from both those areas and the simulated street tree points – was considered the final practical canopy layer.

Summarizing Practical Canopy

To summarize practical canopy results by different geographic units and jurisdiction, we overlaid the layer with a holistic spatial data layer detailed in appendices of Treglia et al. (2021a). Data used in that work were used likewise in this research, with the same general aggregations of land uses from the parcel data as shown in Figure 4B. An exception was that the land use of Open Space and Outdoor Recreation (which included Cemeteries) was lumped with Facilities and Institutions for purposes of displaying the information. These spaces comprised a small portion of the landscape and practical canopy, and were not discernable when displayed as a separate category.

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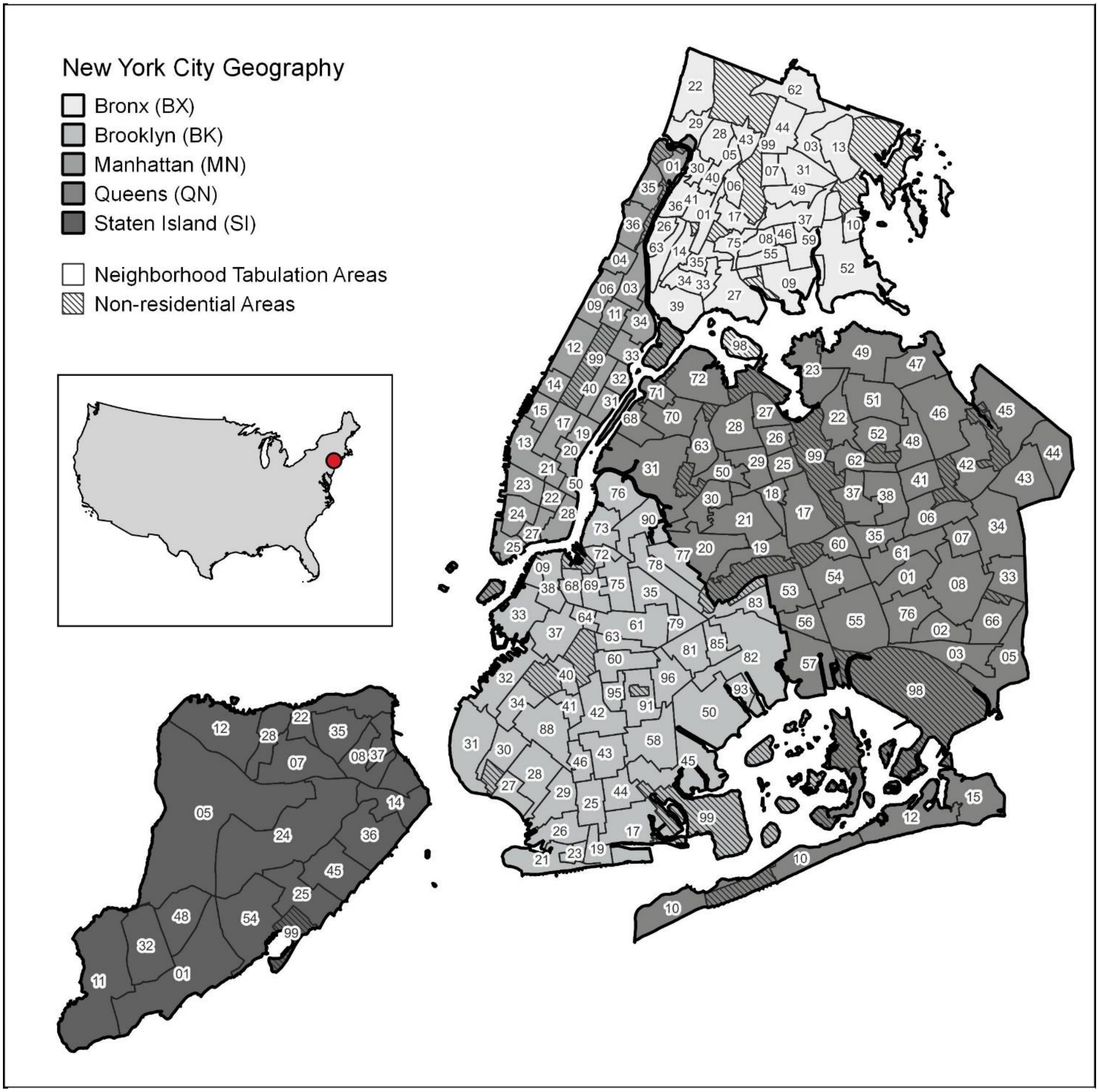
Supplementary Figures



Supplementary Figure 1. Map illustrating main geographic units of New York City used in the paper. Neighborhood Tabulation Areas are referenced in the text using a code comprised of the Borough Code and the borough-specific, two-digit numeric identifier, labeled on the map. The inset depicts where New York City is in relation to the conterminous United States (data from the US Census Bureau). Geographic boundaries for the boroughs of New York City and the Neighborhood Tabulation Areas are from the New York City Department of City Planning.