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Research, part of a Special Feature on Holistic Solutions Based on Nature: Unlocking the Potential of Green and Blue Infrastructure

Examining the distribution of green roofs in New York City through a lens of social, ecological, and technological filters

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ABSTRACT. Green roofs provide multiple benefits including reducing the urban heat island effect, absorbing stormwater and air pollution, and serving as habitat for wildlife. However, many cities have not taken advantage of green roofs as a nature-based solution. In New York City (NYC), approximately 20% of the landscape is covered by buildings, thus rooftops present a substantial opportunity for expanding green infrastructure. Spatial data on green roofs are critical for understanding their abundance and distribution, what filters may drive spatial patterns, and who benefits from them. We describe the development of a green roof dataset for NYC based on publicly available data and classification of aerial imagery from 2016. Of the over one million buildings in NYC, we found only 736 with green roofs (<0.1%), although there may have been others we did not detect. These green roofs are not evenly distributed in NYC - they are most common in midtown and downtown Manhattan, while most other areas have few to none. Green roofs tend to be more prevalent in parts of NYC with combined sewer systems, but some such areas, and those with the most heat-vulnerable communities, have few if any despite their potential to help ameliorate stormwater and urban heat challenges. Though green roofs are providing some benefits within NYC, we anticipate they are filtered based on dynamics of infrastructure, institutions, and perceptions, rather than targeted to address climate and weather-related challenges. There is substantial opportunity in NYC to increase green roofs, and equity of them. The dataset we developed is publicly available and can serve as a baseline for tracking these assets through time, while supporting further research, conversations, and policies related to the benefits and distribution of green roofs. The underlying methods can also be applied to help fill similar data gaps in other cities.

Key Words: *cities, green infrastructure; green roofs; mapping; social-ecological-technical filters; urban remote sensing; urban systems*

INTRODUCTION

In the urban century (Elmqvist et al. 2018, 2019), urban areas are rapidly expanding with dense development that can force out many species and limit opportunities for incorporating nature for both human and non-human benefit (Parnell et al. 2018, United Nations 2018). Cities offer opportunities for sustainability (McPhearson et al. 2021) and can even present opportunities to benefit certain biological taxa such as insect pollinators (Hall et al. 2016), but in areas facing dense development, innovation is needed to increase urban nature and to provide additional nature-based solutions to address a range of urban environmental ills (Kabisch et al. 2017, Keeler et al. 2019, Frantzeskaki et al. 2019). For example, cities can be hot, flood-prone, polluted, and lack accessible and safe spaces for people and biodiversity. Changing the form of cities can ultimately help incorporate nature into them and improve human well-being (McDonald 2015). We examined green roofs as an emerging form of green infrastructure (Grabowski et al. 2017) with potential to provide space for nature in places (rooftops) not regularly considered in urban green space planning.

Green roofs are roofs with vegetation planted in growing media, on top of a waterproof membrane, root barrier, and drainage layers. They can be extensive, with shallow substrates (2–20 cm) and generally with plants selected for stress tolerance (e.g., *Sedum* spp. or *Sempervivum* spp.), or intensive, with deeper substrates (>20 cm) and generally more comparable to a garden at ground level (Oberndorfer et al. 2007). Green roofs provide a myriad of benefits, and as a form of green infrastructure, are sometimes actively planned in cities to help alleviate local challenges (Mell 2011, Keeler et al. 2019, Frantzeskaki et al. 2019, Andersson et al. 2019). As with other forms of green infrastructure, where they can exist and their ultimate benefits depend on various constraints and filters (Andersson et al. 2019). Some cities globally have incentives and policies aimed at increasing the number of and area covered by green roofs, and such efforts can be guided by local needs (McPhearson et al. 2013, Meerow and Newell 2016, 2017, Kremer et al. 2016, Langemeyer et al. 2020), but understanding where green roofs are located is critical for informed decision-making. Data on existing green roofs can also allow for an understanding of how various filters have resulted in the present landscape of this asset and its respective benefits.

Green roofs can provide multiple benefits. Growing media and vegetation components retain stormwater (Mentens et al. 2006). Many cities have combined sewer systems that normally treat both stormwater and sanitary sewage; in heavy precipitation events excess stormwater causes these systems to discharge sewage into local waterways, thus green roofs, among other green infrastructure, can help address this challenge (De Sousa et al. 2012). Green roofs also serve as habitat for biodiversity (Kadas 2006, Parkins 2015, Partridge and Clark 2018), and evapotranspiration by the plants and the low albedo of green roofs help reduce the urban heat island effect (Susca et al. 2011). The multiple layers and moisture of green roofs provide insulation for buildings they are installed on, increasing efficiency for heating and cooling (Gaffin et al. 2010), and the vegetation and growing media can sequester carbon (Getter et al. 2009). Furthermore, green roofs can be made accessible to people, serving as places of respite, recreation, and education. These benefits can ultimately lead to broader public good. For example, cooling and insulation provided by green roofs can potentially improve public health

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outcomes in heatwaves, and improved access to green space can offer mental health benefits (Nutsford et al. 2013). Green roofs may be designed to provide one or more specific benefits while also providing co-benefits. Benefits offered are influenced by specific attributes of individual green roofs (e.g., growing media depth and vegetation type). Who will benefit from green roofs ultimately depends on the services they were designed to provide, along with characteristics of the building and general location (Berardi et al. 2014).

Benefits of green infrastructure are filtered through social, ecological, and technological dimensions of urban systems (Andersson et al. 2015, 2019, 2021, McPhearson et al. 2016, 2022). For example, green roof benefits may be perceived as benefits by some and not others; green roofs may not provide the same quality or quantity of benefits based on underlying infrastructure, and benefits may be influenced by the availability of institutions or local stewards who can provide adequate management to maximize benefits (Andersson et al. 2019). For example, in areas with combined sewer systems, users of impacted waterways may benefit, as will cities required to manage water quality for compliance with environmental regulations. However, actual provisioning of these benefits depends on infrastructure filters: whether green roofs can be installed in geographic areas with combined sewer systems given building constraints such as load bearing capacity (Cascone et al. 2018), and whether they can be built to specifications that contribute substantially as a solution based on factors such as slope (Getter et al. 2007). Institutions also play a role, as centralized goals can drive policies to increase green roofs in areas where they are most needed based on individual criteria or multi-criteria analyses (Langemeyer et al. 2020). Perceptions of residents, property owners, installers, and engineers also influence where green roofs are installed and in what form (e.g., plant palette; Butler et al. 2012). The general cooling benefits of green roofs, with primary beneficiaries being local residents, can similarly be influenced by these filters, and institutional efforts to bring green roofs to scale can likely result in larger, more regional effects (Sun et al. 2016). Increased access to green space provided by green roofs may particularly be influenced by institutional dynamics in terms of who has access to these spaces; perceptions or norms can also play a role in terms of identifying and leveraging opportunities to make green roofs multifunctional. For example, property owners and installers can actively work toward green roofs that absorb stormwater and serve as accessible green spaces. The beneficiaries will vary but could include children attending schools with green roofs, residents of apartment buildings, or the broader community if access is granted, respectively.

Many municipalities have institutional programs for improving environmental quality that can leverage the benefits of green roofs, setting up enabling conditions for broader implementation. For example, Giannoppoulou et al. (2019) reported Basel, Switzerland, has the largest green roof area per capita, largely attributable to incentive programs and construction laws. These programs can be supported by research that has estimated benefits of green roofs and even suggested optimal siting for key benefits. In Xanthi, Greece, for example, simulations have indicated green roofs can provide substantial cooling benefits (Giannopoulou et al. 2019). In both Barcelona (Langemeyer et al. 2020) and Madrid (Velázquez et al. 2019), Spain, recent work has also been developed to support prioritization of new green roofs based on potential benefits. More exhaustive cost-benefit studies have also been conducted, such as work in Atlanta, Georgia, USA (Lamsal 2012). Studies such as these have ultimately helped justify incentives and policies for, and spatial prioritization of, green roofs.

New York City (NYC) has multiple environmental sustainability and human health initiatives including ones developed as part of mayoral initiatives such as PlaNYC (City of New York 2007) and OneNYC (City of New York 2015), as well as programs to minimize stormwater entering combined sewer systems (e.g., a green infrastructure grant program), and to manage the urban heat island effect and the associated morbidity and mortality in the most heat-vulnerable communities (City of New York 2017). Green roofs can be part of the solution, and there are broader efforts to expand them in NYC. As of 2019, there are local laws (NYC Local Laws 92 and 94 of 2019) requiring green roofs or solar panels on nearly all roofs of newly constructed buildings, roofs that are replaced, and buildings undergoing substantial expansion. Furthermore, in 2019 a tax abatement providing financial incentives was renewed and amended (NY Senate Bill S5554B), offering higher abatement rates in priority areas based on a combination of heat vulnerability and potential to reduce stormwater challenges the City faces. Such prioritization can be invaluable, as both environmental challenges and assets are often inequitably distributed within cities (Namin et al. 2020, Locke et al. 2021). Green roofs are expensive to install, and both feasibility and cost effectiveness are influenced by various factors such as structural characteristics of buildings, roof slope, and roof size (Ackerman et al. 2012, Shafique et al. 2018). Thus, we suggest where green roofs exist, and who benefits, has ultimately been filtered by urban development and historical structural factors related to wealth inequality and building characteristics, which result in spatial disparities in this important and growing resource.

Policies and incentives designed to increase green roofs to improve environmental quality should be informed by spatial data, both on environmental quality and green roofs themselves. New York City has some data related to environmental issues including heat vulnerability (Madrigano et al. 2015), combined sewer overflows (e.g., NYC Department of Environmental Protection 2019), and accessibility of parkland (e.g., walking distance to parks, City of New York 2015). The City also tracks some environmental assets including ground level vegetation and tree canopy, captured in high resolution land cover data (available for 2010 and 2017; MacFaden et al. 2012) and individual street trees, inventoried in decennial censuses.

Unlike ground level vegetation, green roofs have not been thoroughly documented across NYC. No single entity has consistently monitored and tracked installations. Prior efforts to capture them have been piecemeal, such as City agencies tracking projects they are involved in and installers sometimes logging them in either their own or industry websites. Aggregating existing data is challenging, given different types of information in different formats. Thus, there have not been sufficient data to enable an understanding of the current and potential roles of green roofs in NYC. Further, cities vary in their tracking of green roofs - a generalizable, more automated approach for mapping them in NYC can also potentially improve broader understanding of this asset.

We specifically fill a data gap in NYC, while providing a workflow that can enable filling of similar data gaps elsewhere. We then illustrate the value of these data by using them to highlight implications of the uneven distribution of green roofs in NYC and discuss potential filters underlying the distribution.

METHODS

Mapping green roofs

Training Data

To identify green roofs in New York City we used a supervised image classification, with subsequent post-processing based on rule-sets and visual inspection. We developed a training dataset for classification primarily based on locations of green roofs for NYC, available from City agencies (NYC Dept. of Environmental Protection and NYC Dept. of Parks and Recreation) and two websites, http://www.greenroofs.com/ and https://greenhomenyc.org/. Datasets were compiled by early 2017 and any without geographic coordinates were geocoded using the Esri World Geocoder. Vegetated surfaces of green roofs were digitized based on 15.2 cm resolution orthoimagery for NYC from 2016, distributed by New York State and the City of New York (available at http://gis.ny.gov/gateway/mg/2016/new_york_city/). Any green roofs noted in the aforementioned sources that we could not visually detect in the orthoimagery were not considered further. Those that we could visually identify, and others that we incidentally encountered, were digitized. We omitted surfaces that were clearly potted plants or other features not integrated into the roof surface, sometimes leveraging supplemental information from web-searches about buildings, and 3-D views in Google Earth and Google Maps. The resulting dataset comprised over 1000 polygons across 155 buildings, covering 11.2 ha of green roofs, used as training data for our classification.

In classifying single land cover types (green roof surfaces in this case), most classification algorithms require training data for non-target classes as well as the main class of interest. Thus, we digitized polygons of non–green roof rooftops, ranging in color, geography, and size to encompass a variety of surfaces with different spectral characteristics (Campbell and Wynne 2011). Particular attention was given to roof types likely to be confused for green roofs given their spectral characteristics, based on exploratory data visualization. These included non-vegetated roofs that were red, green, or very dark in color, as well as artificial turf (e.g., playgrounds) and rooftops covered by other vegetation such as overhanging trees. Strong shadows, for which underlying roof type could not be determined, were also captured. We compiled 272 polygons representing various non–green roof surfaces, covering 1.3 ha. Though balanced training datasets can benefit performance of some classification algorithms and reduce bias (e.g., for random forests; Chawla et al. 2003), we worked with this training sample due to resource constraints.

Imagery and image processing

The imagery we used for classification was the aforementioned 15.2 cm resolution orthoimagery for NYC from 2016, collected from 26 March to 5 April as part of a routine update. The imagery undergoes true orthorectification to remove the appearance of buildings leaning and is comparable to that used for development of a robust planimetric dataset, thus it is of high spatial accuracy. The imagery includes four spectral bands: red; blue; green; and near-infrared. Given the considerable size of the dataset (the extent of the imagery covered 104 billion pixels), we uploaded imagery and other required datasets into Google Earth Engine (GEE; Gorelick et al. 2017) for processing and classification. We also uploaded the building footprint data provided by the City of New York from 30 August 2017 (available at https://data.cityofnewyork.us/Housing-Development/Building-Footprints/nqwf-w8eh) and tree canopy based on a 0.91 m 2010 land cover dataset for NYC (available at https://data.cityofnewyork.us/widgets/9auy-76zt). The building footprint data enabled us to restrict classification to areas occupied by buildings, avoiding potential for confusion with ground-level vegetation, and the land cover data allowed us to mask out tree canopy that overlapped with buildings, which could otherwise be confused for vegetation that is part of green roofs. Scripts used for processing and classification of the imagery in GEE, and training data, are available in a GitHub release at https://github.com/tnc-ny-science/NYC_GreenRoofMapping/releases/tag/1.0.0 and are also provided in Appendices 1–2 of this paper.

From the imagery, we derived the normalized-difference vegetation index (NDVI; Campbell and Wynne 2011) as a new layer to better identify actively photosynthesizing vegetation. We also performed a principal component transformation (Jolliffe 2002) on the image bands to derive new layers; visual inspection indicated the first two principal components helped further separate vegetation in general and were included in classification. Due to computational constraints in GEE, data were analyzed at 0.5 m resolution.

Classification and results refinement

We used a minimum distance classifier based on Mahalanobis distance (Mahalanobis 1936, Sekovski et al. 2014) to classify green roofs and non–green roof surfaces. In preliminary work, we explored performance of various algorithms, both based on visual inspection of results and back-prediction accuracy. In exploratory analysis, some algorithms had very high classification accuracy (e.g., random forest and classification and regression trees had >98% per-pixel classification accuracy based on back-prediction to the original training data), although visual inspection of those results indicated there was severe over-prediction of green roofs across the landscape and the results were not reliable. The Mahalanobis distance classifier, in contrast, had overall per-pixel classification accuracy of 78% but did not exhibit such over-prediction. This accuracy was reasonable given land use and land cover classifications often range about 70–80% accuracy (e.g., Manandhar et al. 2009, Wickham et al. 2013). We also examined performance of the Mahalanobis distance classifier more in-depth to understand transferability of this work, withholding 20% of the full training dataset as a test sample. User's and producer's accuracy for green roof areas, specifically, were 74% and 64%, respectively. Exploratory classifications were evaluated using coarsened imagery (1 m resolution) due to computational constraints.

Recognizing that all results would be visually inspected, we did not use discrete subsets of data for training and testing for the final product but included all data in the classification to maintain the breadth of spectral characteristics represented by training data. For pixels classified as green roofs, we removed clusters smaller than 12.5 m² to eliminate small but numerous false positives of only a few pixels. In our training dataset representing green roofs, smaller polygons did exist but were typically part of larger green roof installations that were captured in the classification. Data were exported from GEE as raster data, and clusters of pixels classified green roof were vectorized as polygons using ArcMap version 10.3.1.

This process yielded 9672 polygons classified as green roof surfaces. To address remaining false positives, we visually inspected all of these polygons by overlaying them with the orthoimagery in QGIS and removed those that did not appear to represent a green roof. For polygons we could not readily discern as a green roof, we also considered earlier imagery (from 2014) as well as imagery in Google Maps and Google Earth. In some cases, we also leveraged photographs from real estate listings found in Google searches for specific addresses. In the process of visual inspection, shapes were adjusted to better fit the general area of green roof surfaces, and additional green roofs incidentally observed based on the 2016 imagery were also added to the dataset to yield as complete a product as possible. All manual refinement was conducted by a single member of our team (MLT), and co-authors inspected results. Lastly, we merged refined results with our original green roof training data to ensure any missed in the classification were in the finalized dataset. Refinement of image classification is commonly used to improve final data products (e.g., Manandhar et al. 2009) and while the manual effort we used was time consuming, it ultimately contributed to a hybrid approach of automated classification and manual refinement that was more efficient than digitization of imagery alone.

Instances of multiple green roof sections per building were merged into MultiPolygon objects, and we added area in square feet as an attribute to the data (in line with the coordinate reference system used and relevant to local users). We included the building footprint area based on the building footprint data, and calculated the proportion of rooftop surface that was green roof. To enable broader use of the dataset, we also added Building ID Number (BIN) and Borough, Block, and Lot Number (BBL) from the Buildings Dataset based on a spatial overlay, and joined fields related to zoning and type of owner from a generalized parcel dataset for NYC (PLUTO/MapPLUTO version 18v1; available at https://www1.nyc.gov/site/planning/data-maps/open-data/bytes-archive.page). For these spatial overlays and all analyses presented, spatial data were created or downloaded in, or reprojected to, a locally appropriate coordinate reference system (New York State Plane, Long Island Zone; EPSG 2263) such that datasets would align and area calculations were locally appropriate.

Examining social, ecological, and technological-infrastructural filters in NYC

The presence of buildings that can accommodate a green roof is a fundamental built infrastructure filter likely to impact the distribution of green roofs in NYC. We characterized green roofs in NYC according to the number and proportion of buildings with green roofs, as well as their area and the proportion of rooftop area consisting of them, across the entire city and by New York City Council District. City Council Districts are relevant for policy and local decision-making, and have fairly consistent population sizes across the 51 units. Though not all buildings are suited to green roofs (e.g., limited roof area, too sloped), analysis of building suitability for them was out of scope for this study and, recognizing these limits, we sought to capture high-level trends and recognize that these infrastructure filters are at play and should be examined more deeply in future research.

Interest in green roofs by different types of owners (e.g., public vs private) and suitability for them in different land use contexts are additional filters that may drive variation in green roof prevalence, size, and type. Further, desire or stated need for green roofs in specific areas to achieve social and ecological benefits, and to mitigate environmental hazards, can also filter where green roofs have been installed and in what form. For example, formal incentive programs like the aforementioned green infrastructure grant program, as well as informal recognition or understanding of their benefits may have influenced the landscape of green roofs documented in our dataset.

We characterized the green roofs in NYC across public vs. private properties and different land uses based on the parcel dataset for NYC, MapPLUTO (version 18v1), informed by inspection of the dataset itself and the metadata. Properties with ownership type coded in MapPLUTO as City or Other Public were considered public, while properties with all other ownership classes were considered private. These data are imperfect, though this breakdown generally captures public vs private ownership. We identified general land uses for properties in which green roofs were identified based on MapPLUTO (buildings on properties with land use of “Park and Open Space” in MapPLUTO were considered as Facilities and Institutions for this work). Given that feasibility for green roofs may vary with building types, land uses, and ownership, and that we do not have a robust understanding of these dynamics, we did not conduct statistical tests in this realm and presented general trends.

The geography of environmental hazards such as high heat exposure can influence spatial prioritization for green roof investments. For example, though green roofs may frequently be installed as real estate amenities, expanding cooling benefits of green roofs in areas with high heat vulnerability is an increasing priority in NYC (e.g., per the priority areas of the aforementioned tax abatement). We examined whether heat risk of communities may have served as a filter influencing the distribution of green roofs by analyzing whether green roofs were more prevalent in areas of the City deemed more heat-vulnerable, based on an index for NYC that characterizes community vulnerability to extreme heat events based on susceptibility of residents to mortality and morbidity in them (building on work described by Madrigano et al. 2015). We used the most recent data available from the New York City Department of Health and Mental Hygiene (representing 2018) in the form of ranked quintiles (1 = least vulnerable; 5 = most vulnerable) at the finest scale available for these data, Neighborhood Tabulation Areas (NTAs; available at http://a816-dohbesp.nyc.gov/IndicatorPublic/VisualizationData.aspx?id=2411,719b87,107,Map,Score,2018). This dataset is not available specifically for City Council Districts; NTAs are smaller than City Council Districts, though generally nested within them. NTAs are designed to have a fairly even number of residents, at minimum 15,000, and they range in size from 51.86 ha to 3040.63 ha (larger areas correspond to lower population densities). Given the finer scale, NTAs also represent more spatial heterogeneity

Table 1. Number and area of green roofs and buildings by property type.

Property Type	Number of Green Roofs	Total Number of Buildings	Green Roof Area (ha)	Total Building Area (ha)
Residential	257	952,393	3.98	9715.25
Mixed-Use (Commercial and Residential)	221	52,950	5.03	1162.10
Facilities and Institutions	127	28,407	10.12	2058.96
Commercial, Manufacturing, Industrial, and Parking	131	44,034	5.50	2830.65

than Council Districts. We identified the highest heat vulnerability value within each City Council District to characterize whether those districts with highly heat-vulnerable populations are being served by green roofs. A 152.4 m inner buffer was applied to the NTA boundaries for this overlay analysis to avoid capturing small slivers of NTAs minimally within Council Districts. We tested for a significant Kendall's τ correlation (Kendall 1938) between the highest HVI in City Council Districts and both proportion of buildings with a green roof and proportion of total rooftop area covered by green roofs using function cor.test() in R, version 3.5.4 (R Core Team 2018).

Green roof investments may also be prioritized in areas with combined stormwater and sanitary sewer systems (combined sewer areas), given the potential for green roofs to absorb stormwater and ultimately reduce overflow events and associated water pollution. Thus, the arrangement of combined sewer areas may act as a filter on the spatial variation in green roofs. We examined this dynamic by comparing the percentage of each City Council District overlapping combined sewer areas from the NYC Department of Environmental Protection with the proportion of buildings and proportion of rooftop area consisting of green roofs. Though ideally analyses would be based on more specific metrics such as volume of combined sewer system discharge attributable to individual areas, no official datasets are released by the City. These sewershed boundaries were made available as part of a summary dataset of 2010 tree canopy and land cover (available at https://data.cityofnewyork.us/Environment/NYC-Urban-Tree-Canopy-Assessment-Metrics-2010/hnxz-kkn5). As with heat vulnerability, we evaluated Kendall's τ. Data used in these analyses, aggregated by City Council District and R code are provided in Appendix 3.

RESULTS AND DISCUSSION

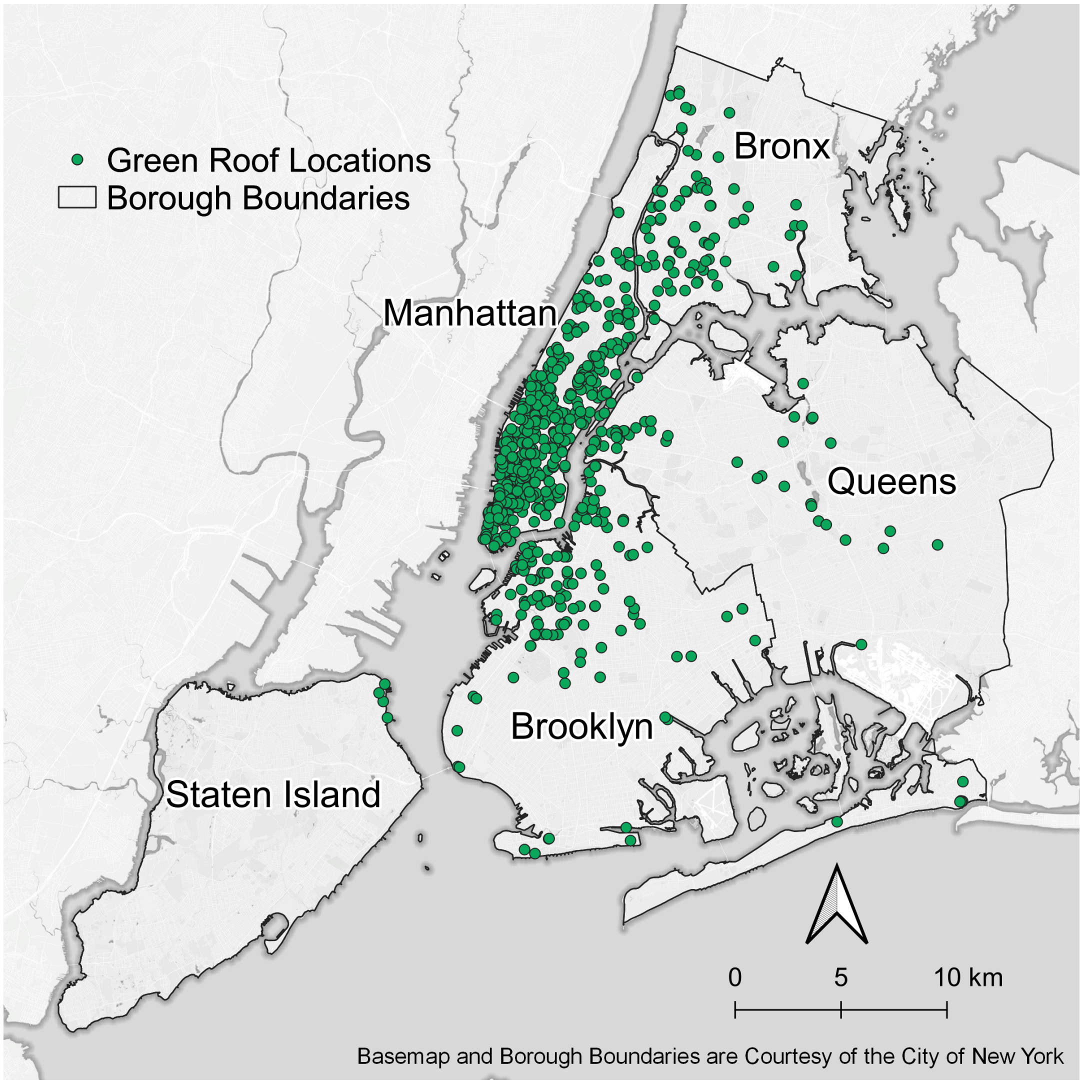
The resulting green roof dataset from this work reflects 736 buildings with green roofs as of 2016 (Fig. 1), covering 24.62 ha of green roof surface. These represent 0.07% of the buildings and 0.15% of rooftop area in NYC. Our study substantially increased the number of green roofs documented, as only 155 green roofs covering 11.94 ha were reported in source data leveraged in this effort. The image classification detected 119 of the 155 green roofs from the training dataset and 569 additional ones we had not previously documented. Of the green roofs in the training data, 13 were smaller than the 12.5 m² minimum size of areas classified as green roof to be further evaluated, thus 84% of the green roofs that could have been detected in the classification were; because the classification was applied on a per-pixel basis, these smaller green roofs still contributed to training the model. Nine more green roofs were added during visual inspection and manual refinement of the classification results. Median green roof size was 109.1 m², and sizes ranged 0.94–25,763.66 m², with the distribution highly right skewed (very few large green roofs). The green roof dataset is available via the online data repository, Zenodo, at https://zenodo.org/record/1469674 (Treglia et al. 2018), where updates can be deposited and versioned. Google Earth Engine Code used and training data are available on GitHub, at https://github.com/tnc-ny-science/NYC_GreenRoofMapping/releases/tag/1.0.0, as well as in Appendices 1–2 of this paper.

Manual refinement of the classification improved our results, eliminated false positives, and detected at least some false negatives. We acknowledge there may have been false negatives in our analysis (i.e., green roofs that are present but not detected) that we are unable to fully quantify. As additional validation, we reviewed our results with the Green Roof Researchers Alliance, a group of individuals from various institutions that are knowledgeable about green roofs in NYC, before release. No substantial omissions or over-estimations were identified in this process. If implemented, systematic tracking of green roof installations (e.g., by a City agency) would enable additional verification of analyses like ours. The dataset we generated indicates the distribution of green roofs is uneven across New York City (Figs. 1, 2a). Over one half numerically (414) and nearly one half by area (12.21 ha) were concentrated in six contiguous City Council Districts within Manhattan, from the southern boundary of the borough through approximately the Upper East and Upper West sides. Even in other boroughs, green roofs were often concentrated closer to these parts of Manhattan. Overall, eight districts out of 51 total had no green roofs, and more than half (27) had only between 1 and 10.

Of the 14,478 publicly owned properties in NYC, 73 (0.5%) had a green roof, and of the 843,090 privately owned properties, 663 had a green roof (0.07%). Thus, green roofs were proportionally more common on public buildings. In terms of land use, most green roofs occur on private, residential, and mixed commercial/residential buildings, followed by commercial buildings (Table 1). The largest cumulative area of green roofs by land use type was on institutional properties. The green roofs in this category included the largest ones in NYC, on the Jacob Javits Convention Center (2.58 ha) and Barclays Center (1.19 ha), which is a large venue for sports and other events, in addition to those on universities, and City-owned buildings such as recreation centers run by the NYC Department of Parks and Recreation.

We found no association, positive or negative, between the distribution of green roofs and the maximum heat vulnerability index observed within City Council Districts, (see maps, Fig. 2a, b). There was no significant correlation with either the proportion of buildings covered by green roofs or the proportion of rooftop area composed of green roofs (proportion of green roofs: τ =

Fig. 1. Estimated locations of green roofs in New York City based on aggregation of existing data, remote sensing analysis, and manual refinement.

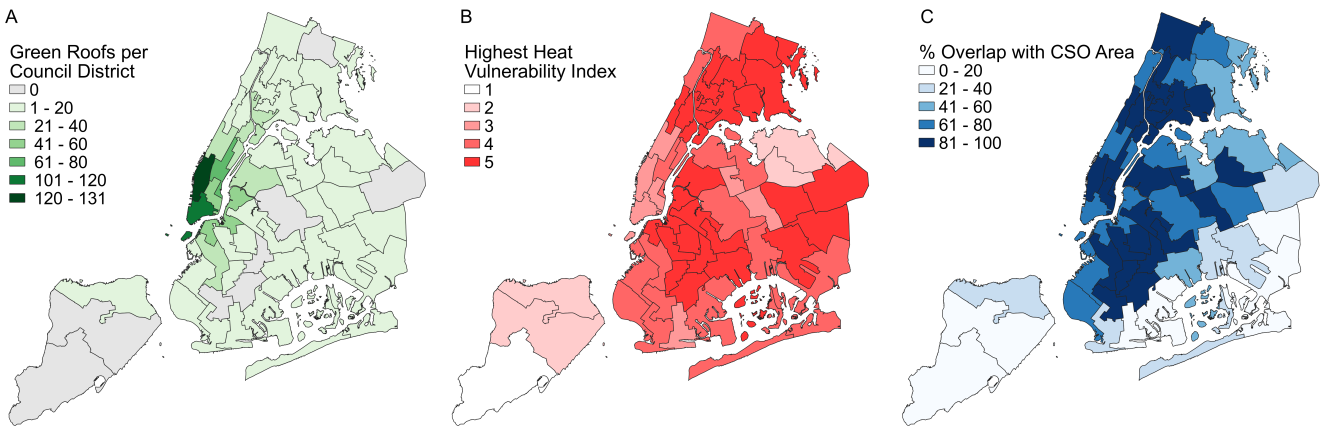


0.009, z = 0.09, p = 0.93; proportion of rooftop area consisting of green roofs: τ = -0.08, z = -0.73, p = 0.46). Notably, areas with populations identified as most heat-vulnerable are generally not well served by green roofs. None of the aforementioned City Council Districts in midtown and downtown Manhattan, which in aggregate contained more than half of the green roofs in NYC, overlap NTAs ranked as the most heat-vulnerable; 22 City Council Districts overlap NTAs ranked as the most heat-vulnerable, though over half of these had less than 10 green roofs, and four had none. These numbers translate to a small portion of buildings with green roofs, with the highest percentage of green roofs among these Council Districts being 0.50%.

In contrast to heat vulnerability, the prevalence of green roofs was positively correlated with the percentage of City Council District area overlapping combined sewershed areas, based on both the proportion of buildings with a green roof and the proportion of rooftop area with green roofs (Fig. 2a, c), (proportion of buildings with green roofs: τ = 0.25, z = 2.59, p = 0.01; proportion of rooftop area consisting of green roofs: τ = 0.20, z = 2.10, p = 0.04). The relationship, while significant, was relatively weak, and both the number and area of green roofs was small; the highest percentage of buildings with a green roof among Council Districts that overlap with priority sewershed areas was 1.9% (occupying 0.84% of rooftop area) in the southern part of Manhattan. Furthermore, there were various exceptions to the trend, for example, of 37 Council Districts with over 50% overlap with priority sewershed areas, five had none and five had only one.

Though not all buildings may be suitable for green roofs, we anticipate there is substantial capacity to increase them in number, area, and distribution, with potential to provide benefits to areas that need them the most. The dataset we developed can serve as a baseline to facilitate tracking change through time, and it can be leveraged for additional research. These data can also inform

Fig. 2. A) Percentage of buildings with a green roof by New York City Council District, B) the highest heat vulnerability at the scale of Neighborhood Tabulation Areas within each City Council District (as of 2018), and C) the estimated percentage of overlap for each City Council District with combined sewer system areas.



policy, management of environmental challenges, and advocacy to increase green roofs and equity of them in NYC. While our work was specific to NYC, the general methodology we employed can be leveraged in other cities, and respective datasets can be used to similarly compare the distribution of green roofs relative to the need for their benefits. Our exploratory classifications suggested that in future work, both in NYC and elsewhere, careful attention should be paid to the training data. For example, in subsetting data to evaluate performance on separate testing and training datasets, we found per-pixel accuracy decreased both overall and for the test dataset. Thus, the broader spectral variability in the entire training dataset supported higher accuracy.

As with most forms of green infrastructure, we anticipate the distribution of green roofs, and their benefits, is filtered by a combination of infrastructure, institutions, and perceptions (Andersson et al. 2019). As has been shown in other cities (e.g., Grunwald et al. 2017, Giannopoulou et al. 2019), infrastructure considerations such as size, age, height, and other technical factors of buildings likely contribute to where green roofs have been and can be installed in NYC. Environmental benefits are strongly filtered by the type of roof (intensive or extensive), which is also associated with soil depth, and thus this ecological factor is affected by the underlying infrastructure and its ability to support the weight of green roofs (Oberndorfer et al. 2007, Getter et al. 2009). The benefits ultimately realized also depend on spatial distribution of green roofs compared to the need for them (e.g., Velázquez et al. 2019, Langemeyer et al. 2020). For example, are green roofs installed in areas that would benefit the most, given stormwater or urban heat challenges, or where there is limited access to green space? Institutional filters such as policies and incentive programs can also play a key role - incentives for specific, individual benefits (e.g., stormwater management) may bias aspects of design and siting of green roofs at the expense of other benefits. Furthermore, social goals and perceptions around green roofs can influence what types of green roofs are built, what functions they are designed for, and how multifunctional and accessible they are (Jungels et al. 2013, Vanstockem et al. 2018, Sarwar and Alsaggaf 2020).

Green roofs in NYC include urban farms for food production, sedum roofs primarily designed for cooling and stormwater absorption, recreational green roofs on residential buildings that serve as spaces for socializing, as well as green roofs on top of schools that serve numerous purposes (Fig. 3). These contexts have influenced the siting and form of green roofs in NYC, subsequently filtering the benefits. The green roof dataset described herein can ultimately enable further research on how factors such as age of buildings, slope of roofs, household income, real estate value, and local interests are acting as filters on where green roofs are installed, their form, and the benefits realized. It may even be possible to infer causal relationships, which could inform policy interventions, incentive programs, building or green roof design alterations that can support installation of green roofs more broadly, and realization of their benefits more where they are most needed. Functionally, with better information on these filters, it may be possible to change how they operate. This work can also support spatial prioritization of green infrastructure that can be conducted using tools like multi-criteria analysis (Meerow and Newell 2017, Langemeyer et al. 2020), though the actual future of green roofs and their benefits will depend on infrastructure dynamics, institutional considerations, and perceptions of stakeholders involved, which warrant further research.

Our results suggest social, infrastructural, and economic filters play out spatially in NYC, with most green roofs concentrated in midtown and downtown Manhattan, which tend to have residents with higher incomes (e.g., Lazar et al. 2016). Thus, where green roofs exist may be driven by factors such as wealth (who can afford a green roof) and building characteristics related to feasibility of installing them. These dynamics functionally filter who benefits, and whether environmental challenges are being addressed through green roofs in equitable ways. Based on these data, green

Fig. 3. Example green roofs in New York City showcasing a diversity of green roof applications, including, top row: Brooklyn Grange rooftop farm in the Brooklyn Navy Yard used for production agriculture, and bottom row: diverse meadow and recreation space on the green roof at Vice Media HQ in Williamsburg, Brooklyn (photo credits: Timon McPhearson).

roofs are filtered such that they have not been installed as frequently in the most heat-vulnerable communities of NYC as other areas, despite their ability to provide cooling benefits and additional insulation on buildings. In contrast, green roofs have been installed more frequently in areas dominated by combined sewer systems, albeit they comprise a small portion of the rooftops and rooftop area. Areas with the highest prevalence of green roofs are densely built and consist largely of impermeable surfaces, thus green roofs can provide benefits there. However, these areas may not be the ones that stand to gain the most based on specific considerations such as heat vulnerability. We anticipate some areas of NYC, such as most of Staten Island, northern Bronx, and eastern Queens, are generally less able to support green roofs, given that they anecdotally consist of lower-density residential neighborhoods with steep-sloped, peaked roofs. However, areas such as the southern Bronx and eastern Brooklyn, both with low prevalence of green roofs and higher heat vulnerability, consist of higher density development with larger, flat-roofed buildings that may be more suitable.

Green roofs also appear to be filtered by institutional dynamics related to building ownership and type, although with so few green roofs installed in NYC it is challenging to draw rigorous conclusions. The trends we observe, with proportionately more green roofs installed on public buildings, may partly be a consequence of associated building type. For example, publicly owned properties generally do not include 1–2 family houses, often with peaked roofs, which comprise a large portion of the private building stock and may not be feasible or cost-effective for green roofs. Though most of the green roofs, numerically, are installed on residential buildings, those buildings are generally apartmentment buildings. The trend of proportionally more green roofs on public buildings may also be related to economies of scale in that it can be more feasible or cost-effective for a single entity with many buildings, like a City agency, to install green roofs more broadly. For example, the NYC Department of Parks and Recreation alone maintains about 1.8 ha of green roofs on buildings they manage (https://www.nycgovparks.org/greening/sustainable-parks/green-roofs). Institutional buildings in both public and private sectors are also often large, as with recreation centers, convention centers, and university campuses. Thus, while few have green roofs in aggregate compared to residential properties, they represent a large portion of the green roof area in the city. Given the small number of green roofs in NYC, we anticipate there is substantial opportunity to increase them on various building types, both publicly- and privately-owned.

To fully understand how underutilized green roofs are across buildings in NYC, future work will benefit from robust estimates of potential for buildings to support them. Earlier work has estimated that 5701 buildings with large rooftops (≥ 0.093 ha) could support production-scale rooftop agriculture (Ackerman et al. 2012). However, we anticipate many more buildings could support green roofs in general, with no limit on minimum size and potential for shallower growing media, thus less weight to bear. This gap in information on realistic potential for green roofs also limits some of our analyses herein. Ideally, our analyses of the distribution of green roofs across the City, by City Council District, and across public and private lands, would be based on the proportion of buildings (or area) suitable for green roofs. Without such a dataset, there is no perfect way to standardize these data, and any approach has various underlying assumptions. Some of the trends we observe are likely based, in part, on the variability of building type across NYC and where there are buildings that can support a green roof. Efforts to fill this gap may build on similar work, such as in Xanthi, Greece (Giannopoulou et al. 2019), and Braunschweig, Germany (Grunwald et al. 2017).

As with development of any new dataset, limits are important to name for potential users. First, this dataset represents a specific point in time, late March and early April 2016, when the imagery underlying our analysis was collected. Since then, more green roofs have been installed, and some have been removed, thus updates of these data will be critical to maintaining a robust understanding of the green roof landscape in NYC. While we are generally confident in the dataset we produced and have had validation of this from dataset users within City agencies and other organizations, there were limits in our ability to accurately discern green roofs from other roof types. We used the best available data and multiple sources to verify green roofs that were detected through image classification as possible, though it is possible that some rooftops that were heavily vegetated with potted plants were inadvertently included. We recognize extremely small green roof patches (<12.5 m^2) were generally not captured based on parameters of the classification work, and areas that were heavily shadowed were difficult to discern. Thus, this is the most complete green roof dataset for NYC to date, and it should be taken as an estimate rather than a complete census, recognizing potential for additional green roofs we did not detect. Further, our work does not capture specific details about green roofs such as depth of growing media and vegetation type, which relate to benefits. Ongoing and future efforts can help fill these data gaps, which will allow more accurate estimates of the benefits green roofs are providing.

CONCLUSION

In this study we mapped green roofs in NYC by classifying aerial imagery and manually refining the results, resulting in the most comprehensive dataset of this type for NYC. We detected only 736 green roofs covering about 25 ha, out of over one million buildings with a total footprint of nearly 16,000 ha. Overall, less than 0.01% of buildings, and 0.16% of rooftop area in NYC were identified as having a green roof. While not all buildings are suitable for green roofs, and there may have been green roofs we did not detect in this study, we anticipate there is substantial opportunity to increase the number and area of green roofs within NYC. Our results indicate that green roofs are not evenly distributed across the landscape, with the highest number and overall prevalence in midtown and downtown Manhattan. This uneven distribution is likely driven by various filters and influences where benefits of green roofs are realized given variability in local conditions. We found no relationship between prevalence of green roofs and heat vulnerability of communities, despite the potential for green roofs to help ameliorate threats of extreme heat. However, there tends to be higher prevalence of green roofs in City Council Districts overlapping larger portions of combined-sewer sewersheds, indicating that the distribution is conducive to helping address stormwater management challenges that NYC faces.

This study fills a data gap for NYC, establishing a baseline understanding of green roofs that can be leveraged and built on in future work. For example, this dataset can be used to develop spatially explicit estimates of benefits, support advocacy efforts for more equitable green infrastructure, and it can be used to better understand filters that affect the distribution of green roofs. Though we focus specifically on NYC, many cities lack robust data on green roofs, and our approach can be applied to fill similar gaps elsewhere. Filling these data gaps can allow a more robust understanding of what factors drive the siting of green roofs, who has access to them, what benefits they provide, and how these benefits are filtered by social, ecological, and technological characteristics of the building, neighborhood, and broader community. Thus, improved data on green roofs, as we provide here, can support efforts in cities to improve the equity of green infrastructure planning and implementation, and to support city and community efforts to ensure that neighborhoods with the greatest need for the benefits of cooling, stormwater absorption, and access to green space, are prioritized for green roof and other green infrastructure investments.

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Data Availability:

Data used in this study are generally publicly available at sources referenced in the text. The main resultant dataset of this work, representing estimated green roof footprints for New York City, NY, USA, is available on Zenodo at https://zenodo.org/record/1469674 . Code used to help develop this dataset within Google Earth Engine, and training data are available within a release in a GitHub Repository at https://github.com/tnc-ny-science/NYC_GreenRoofMapping/releases/tag/1.0.0 and these materials are also available as appendices with this manuscript. Summarized data used for correlation analyses presented with associated R code are also available as appendices.

LITERATURE CITED

Ackerman, K., R. Plunz, M. Conard, and R. Katz. 2012. The potential for urban agriculture in New York City. Urban Design Lab, Earth Institute, Columbia University, New York, NY, USA.

Andersson, E., S. Borgström, D. Haase, J. Langemeyer, A. Mascarenhas, T. McPhearson, M. Wolff, E. Łaszkiewicz, J. Kronenberg, D. N. Barton, and P. Herreros-Cantis. 2021. A context sensitive systems approach for understanding and enabling ecosystem service realisation in cities. Ecology and Society 26(2):35. https://doi.org/10.5751/ES-12411-260235

Andersson, E., J. Langemeyer, S. Borgström, T. McPhearson, D. Haase, J. Kronenberg, D. N. Barton, M. Davis, S. Naumann, L. Röschel, and F. Baró. 2019. Enabling green and blue infrastructure to improve contributions to human well-being and equity in urban systems. BioScience 69(7):566-574. https://doi.org/10.1093/biosci/biz058

Andersson, E., T. McPhearson, P. Kremer, E. Gomez-Baggethun, D. Haase, M. Tuvendal, and D. Wurster. 2015. Scale and context dependence of ecosystem service providing units. Ecosystem Services 12:157-164. https://doi.org/10.1016/j.ecoser.2014.08.001

Berardi, U., A. GhaffarianHoseini, and A. GhaffarianHoseini. 2014. State-of-the-art analysis of the environmental benefits of green roofs. Applied Energy 115:411-428. https://doi.org/10.1016/j.apenergy.2013.10.047

Butler, C., E. Butler, and C. M. Orians. 2012. Native plant enthusiasm reaches new heights: Perceptions, evidence, and the future of green roofs. Urban forestry & urban greening 11(1):1-10. https://doi.org/10.1016/j.ufug.2011.11.002

Campbell, J. B., and R. H. Wynne. 2011. Introduction to Remote Sensing. Fifth edition. The Guilford Press, New York, NY, USA. https://doi.org/10.1080/10106048709354126

Cascone, S., F. Catania, A. Gagliano, and G. Sciuto. 2018. A comprehensive study on green roof performance for retrofitting existing buildings. Building and Environment 136:227-239. https://doi.org/10.1016/j.buildenv.2018.03.052

Chawla, N. V., A. Lazarevic, L. O. Hall, and K. W. Bowyer. 2003. SMOTEBoost: Improving Prediction of the Minority Class in Boosting. Pages 107-119 in N. Lavrač, D. Gamberger, L. Todorovski, and H. Blockeel, editors. Knowledge Discovery in Databases: PKDD 2003. Springer Berlin Heidelberg. https://doi.org/10.1007/978-3-540-39804-2_12

City of New York. 2007. PlaNYC: A greener, greater New York. Strategic Plan, Office of the Mayor, New York, NY, USA.

City of New York. 2015. One New York: The plan for a strong and just city. Strategic Plan, Office of the Mayor, New York, NY, USA.

City of New York. 2017. Cool neighborhoods NYC: A comprehensive approach to keep communities safe in extreme heat. Strategic Plan, New York City Mayor's Office of Recovery and Resiliency, New York, NY, USA.

De Sousa, M. R., F. A. Montalto, and S. Spatari. 2012. Using life cycle assessment to evaluate green and grey combined sewer overflow control strategies. Journal of Industrial Ecology 16 (6):901-913. https://doi.org/10.1111/j.1530-9290.2012.00534.x

Elmqvist, T., E. Andersson, N. Frantzeskaki, T. McPhearson, P. Olsson, O. Gaffney, K. Takeuchi, and C. Folke. 2019. Sustainability and resilience for transformation in the urban century. Nature Sustainability 2(4):267-273. https://doi.org/10.1038/s41893-019-0250-1

Elmqvist, T., X. Bai, N. Frantzeskaki, C. Griffith, D. Maddox, T. McPhearson, S. Parnell, P. Romero-Lankao, D. Simon, and M. Watkins, editors. 2018. The Urban Planet: Knowledge Towards Sustainable Cities. Cambridge University Press, Cambridge, England. https://doi.org/10.1017/9781316647554

Frantzeskaki, N., T. McPhearson, M. J. Collier, D. Kendal, H. Bulkeley, A. Dumitru, C. Walsh, K. Noble, E. van Wyk, C. Ordóñez, C. Oke, and L. Pintér. 2019. Nature-based solutions for urban climate change adaptation: linking science, policy, and practice communities for evidence-based decision-making. BioScience 69(6):455-466. https://doi.org/10.1093/biosci/biz042

Gaffin, S., C. Rosenzweig, J. Eichenbaum-Pikser, R. Khanbilvardi, and T. Susca. 2010. A temperature and seasonal energy analysis of green, white, and black roofs. Center for Climate Systems Research, Columbia University, New York, Technical Report.

Getter, K. L., D. B. Rowe, and J. A. Andresen. 2007. Quantifying the effect of slope on extensive green roof stormwater retention. Ecological Engineering 31(4):225-231. https://doi.org/10.1016/j.ecoleng.2007.06.004

Getter, K. L., D. B. Rowe, G. P. Robertson, B. M. Cregg, and J. A. Andresen. 2009. Carbon sequestration potential of extensive green roofs. Environmental Science & Technology 43 (19):7564-7570. https://doi.org/10.1021/es901539x

Giannopoulou, M., A. Roukouni, and K. Lykostratis. 2019. Exploring the benefits of urban green roofs: a GIS approach applied to a Greek city. CES Working Papers 11(1):55-72.

Gorelick, N., M. Hancher, M. Dixon, S. Ilyushchenko, D. Thau, and R. Moore. 2017. Google Earth Engine: Planetary-scale geospatial analysis for everyone. Remote Sensing of Environment 202:18-27 https://doi.org/10.1016/j.rse.2017.06.031

Grabowski, Z. J., A. M. Matsler, C. Thiel, L. McPhillips, R. Hum, A. Bradshaw, T. Miller, and C. Redman. 2017. Infrastructures as socio-eco-technical systems: five considerations for interdisciplinary dialogue. Journal of Infrastructure Systems 23(4):02517002. https://doi.org/10.1061/(ASCE)IS.1943-555X.0000383

Grunwald, L., J. Heusinger, and S. Weber. 2017. A GIS-based mapping methodology of urban green roof ecosystem services applied to a Central European city. Urban Forestry & Urban Greening 22:54-63. https://doi.org/10.1016/j.ufug.2017.01.001

Hall, D. M., G. R. Camilo, R. K. Tonietto, D. H. Smith, J. Ollerton, K. Ahrné, M. Arduser, J. S. Ascher, K. C. R. Baldock, R. Fowler, G. Frankie, D. Goulson, B. Gunnarsson, M. E. Hanley, J. I. Jackson, G. Langellotto, D. Lowenstein, E. S. Minor, S. M. Philpott, S. G. Potts, M. H. Sirohi, E. M. Spevak, G. N. Stone, and C. G. Threlfall. 2016. The city as a refuge for insect pollinators. Conservation Biology 31(1):24-29. https://doi.org/10.1111/cobi.12840

Jolliffe, I. T. 2002. Principal Component Analysis. Springer-Verlag, New York, NY, USA.

Jungels, J., D. A. Rakow, S. B. Allred, and S. M. Skelly. 2013. Attitudes and aesthetic reactions toward green roofs in the northeastern United States. Landscape and Urban Planning 117:13-21. https://doi.org/10.1016/j.landurbplan.2013.04.013

Kabisch, N., H. Korn, J. Stadler, and A. Bonn. 2017. Nature-based solutions to climate change adaptation in urban areas: Linkages between science, policy and practice. Springer Nature. https://doi.org/10.1007/978-3-319-56091-5

Kadas, G. 2006. Rare invertebrates colonizing green roofs in London. Urban habitats 4(1):66-86.

Keeler, B. L., P. Hamel, T. McPhearson, M. H. Hamann, M. L. Donahue, K. A. Meza Prado, K. K. Arkema, G. N. Bratman, K. A. Brauman, J. C. Finlay, A. D. Guerry, S. E. Hobbie, J. A. Johnson, G. K. MacDonald, R. I. McDonald, N. Neverisky, and S. A. Wood. 2019. Social-ecological and technological factors moderate the value of urban nature. Nature Sustainability 2 (1):29-38. https://doi.org/10.1038/s41893-018-0202-1

Kendall, M. G. 1938. A new measure of rank correlation. Biometrika 30(1-2):81-93. https://doi.org/10.1093/biomet/30.1-2.81

Kremer, P., Z. A. Hamstead, and T. McPhearson. 2016. The value of urban ecosystem services in New York City: A spatially explicit multicriteria analysis of landscape scale valuation scenarios. Environmental Science & Policy 62:57-68. https://doi.org/10.1016/j.envsci.2016.04.012

Lamsal, M. 2012. Green roof adoption: A GIS-integrated cost-benefit analysis in Atlanta incorporating a positive externality. Thesis for M.S., University of Georgia, Athens, GA, USA.

Langemeyer, J., D. Wedgwood, T. McPhearson, F. Baró, A. L. Madsen, and D. N. Barton. 2020. Creating urban green infrastructure where it is needed - A spatial ecosystem service-based decision analysis of green roofs in Barcelona. Science of The Total Environment 707:135487. https://doi.org/10.1016/j.scitotenv.2019.135487

Lazar, R., J. Pinchoff, J. Fuld, L. Chen, and S. K. Greene. 2016. Neighborhood poverty and infectious disease: health disparities in New York City. New York City Department of Health and Mental Hygiene (68), New York City, NY, USA.

Locke, D. H., B. Hall, J. M. Grove, S. T. A. Pickett, L. A. Ogden, C. Aoki, C. G. Boone, and J. P. M. O'Neil-Dunne. 2021. Residential housing segregation and urban tree canopy in 37 US Cities. npj Urban Sustainability 1(1):15. https://doi.org/10.1038/s42949-021-00022-0

MacFaden, S. W., J. P. O'Neil-Dunne, A. R. Royar, J. W. Lu, and A. G. Rundle. 2012. High-resolution tree canopy mapping for New York City using LIDAR and object-based image analysis. Journal of Applied Remote Sensing 6(1):063567-1. https://doi.org/10.1117/1.JRS.6.063567

Madrigano, J., K. Ito, S. Johnson, P. L. Kinney, and T. Matte. 2015. A case-only study of vulnerability to heat wave-related mortality in New York City (2000-2011). Environmental health perspectives 123(7):672-678. https://doi.org/10.1289/ehp.1408178

Mahalanobis, P. 1936. On the generalized distance in statistics. Proceedings of the National Institute of India 12:49-55.

Manandhar, R., I. O. A. Odeh, and T. Ancev. 2009. Improving the accuracy of land use and land cover classification of landsat data using post-classification enhancement. Remote Sensing 1(3). https://doi.org/10.3390/rs1030330

McDonald, R. I. 2015. Conservation for Cities: How to Plan & Build Natural Infrastructure. Island Press, Washington, DC., USA.

McPhearson, T., P. Kremer, and Z. A. Hamstead. 2013. Mapping ecosystem services in New York City: Applying a social-ecological approach in urban vacant land. Ecosystem Services 5:11-26. https://doi.org/10.1016/j.ecoser.2013.06.005

McPhearson, T., S. T. A. Pickett, N. B. Grimm, J. Niemelä, M. Alberti, T. Elmqvist, C. Weber, D. Haase, J. Breuste, and S. Qureshi. 2016. Advancing urban ecology toward a science of cities. BioScience 66(3):198-212. https://doi.org/10.1093/biosci/biw002

McPhearson, T., C. M. Raymond, N. Gulsrud, C. Albert, N. Coles, N. Fagerholm, M. Nagatsu, A. S. Olafsson, N. Soininen, and K. Vierikko. 2021. Radical changes are needed for transformations to a good Anthropocene. npj Urban Sustainability 1(1):5. https://doi.org/10.1038/s42949-021-00017-x

McPhearson, T., E. Cook, M. Berbés-Blázquez, C. Cheng, N.B. Grimm, E. Andersson, O. Barbosa, D.G. Chandler, H. Chang, M. Chester, D. Childers, S. Elser, N. Frantzeskaki, Z. Grabowski, P. Groffman R.L. Hale, D.M. Iwaniec, N. Kabisch, C. Kennedy, S.A. Markolf, A.M. Matsler, L.E. McPhillips, T.R. Miller, T.A. Muñoz-Erickson, E. Rosi, T.G. Troxler. 2022. A social-ecological-technological systems approach to urban ecosystem services. One Earth 5(50):505-518. https://doi.org/10.1016/j.oneear.2022.04.007

Meerow, S., and J. P. Newell. 2016. Urban resilience for whom, what, when, where, and why? Urban Geography 40(3):309-329. https://doi.org/10.1080/02723638.2016.1206395

Meerow, S., and J. P. Newell. 2017. Spatial planning for multifunctional green infrastructure: Growing resilience in Detroit. Landscape and Urban Planning 159:62-75. https://doi.org/10.1016/j.landurbplan.2016.10.005

Mell, I. C. 2011. Green infrastructure planning: a contemporary approach for innovative interventions in urban landscape management. Journal of biourbanism 1(1):29-39.

Mentens, J., D. Raes, and M. Hermy. 2006. Green roofs as a tool for solving the rainwater runoff problem in the urbanized 21st century? Landscape and Urban Planning 77(3):217-226. https://doi.org/10.1016/j.landurbplan.2005.02.010

Namin, S., W. Xu, Y. Zhou, and K. Beyer. 2020. The legacy of the Home Owners' Loan Corporation and the political ecology of urban trees and air pollution in the United States. Social Science & Medicine 246:112758. https://doi.org/10.1016/j.socscimed.2019.112758

Nutsford, D., A. L. Pearson, and S. Kingham. 2013. An ecological study investigating the association between access to urban green space and mental health. Public Health 127(11):1005-1011. https://doi.org/10.1016/j.puhe.2013.08.016

NYC Department of Environmental Protection. 2019. Combined Sewer Overflows Best Management Practices Annual Report For The Period January 1, 2018 - December 31, 2018: 14 Wastewater Resource Recovery Facilities' SPDES Permits. New York City, NY, USA.

Oberndorfer, E., J. Lundholm, B. Bass, R. R. Coffman, H. Doshi, N. Dunnett, S. Gaffin, M. Köhler, K. K. Y. Liu, and B. Rowe. 2007. Green roofs as urban ecosystems: ecological structures, functions, and services. BioScience 57(10):823-833. https://doi.org/10.1641/B571005

Parkins, K. L. 2015. Bats in New York City: An acoustic survey and the role of green roofs. Thesis for M.S., Fordham University, Bronx, NY, USA.

Parnell, S., T. Elmqvist, T. McPhearson, H. Nagendra, and S. Sörlin. 2018. The Urban Planet: Knowledge Towards Sustainable Cities. Pages 1-16 in Introduction: Situating Knowledge and Action for an Urban planet. Cambridge University Press, Cambridge, UK. https://doi.org/10.1017/9781316647554.002

Partridge, D. R., and J. A. Clark. 2018. Urban green roofs provide habitat for migrating and breeding birds and their arthropod prey. PLOS ONE 13(8):e0202298. https://doi.org/10.1371/journal.pone.0202298

R Core Team. 2018. R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. URL: http://www.R-project.org/.

Sarwar, S., and M. I. Alsaggaf. 2020. The willingness and perception of people regarding green roofs installation. Environmental Science and Pollution Research 27(20):25703-25714. https://doi.org/10.1007/s11356-020-08511-y

Sekovski, I., F. Stecchi, F. Mancini, and L. Del Rio. 2014. Image classification methods applied to shoreline extraction on very high-resolution multispectral imagery. International Journal of Remote Sensing 35(10):3556-3578. https://doi.org/10.1080/01431161.2014.907939

Shafique, M., R. Kim, and M. Rafiq. 2018. Green roof benefits, opportunities and challenges - A review. Renewable and Sustainable Energy Reviews 90:757-773. https://doi.org/10.1016/j.rser.2018.04.006

Sun, T., C. Grimmond, and G. Ni. 2016. How do green roofs mitigate urban thermal stress under heat waves? Journal of Geophysical Research. Atmospheres 121(10):5320-5335. https://doi.org/10.1002/2016JD024873

Susca, T., S. R. Gaffin, and G. R. Dell'Osso. 2011. Positive effects of vegetation: Urban heat island and green roofs. Environmental Pollution 159(8-9):2119-2126. https://doi.org/10.1016/j.envpol.2011.03.007

Treglia, M. L., T. McPhearson, E. W. Sanderson, G. Yetman, and E. N. Maxwell. 2018. Green roofs footprints for New York City, assembled from available data and remote sensing (Version 1.0.0) [Data set]. Zenodo.

United Nations. 2018. 2018 Revision of World Urbanization Prospects. Department of Economic and Social Affairs, Population Division, New York, USA.

Vanstockem, J., L. Vranken, B. Bleys, B. Somers, and M. Hermy. 2018. Do looks matter? A case study on extensive green roofs using discrete choice experiments. Sustainability 10(2). https://doi.org/10.3390/su10020309

Velázquez, J., P. Anza, J. Gutiérrez, B. Sánchez, A. Hernando, and A. García-Abril. 2019. Planning and selection of green roofs in large urban areas. Application to Madrid metropolitan area. Urban green infrastructure - connecting people and nature for sustainable cities 40:323-334. https://doi.org/10.1016/j.ufug.2018.06.020

Wickham, J. D., S. V. Stehman, L. Gass, J. Dewitz, J. A. Fry, and T. G. Wade. 2013. Accuracy assessment of NLCD 2006 land cover and impervious surface. Remote Sensing of Environment 130 (0):294-304. https://doi.org/10.1016/j.rse.2012.12.001

Appendix 1. Google Earth Engine code used for classification of green roofs from aerial imagery. Subsequent steps were taken to arrive at the final dataset, described in the text of the manuscript.

Please click here to download file 'appendix1.txt'.

Appendix 2. Training Data used for classification of green roofs from aerial imagery. Development of these data are described in the text of the manuscript.

Please click here to download file 'appendix2.zip'.

Appendix 3. Summarized data of green roofs, heat vulnerability, and estimated proportion of area covered by combined sewer area for City Council Districts, and R code used to run correlation analyses presented in the manuscript.

Please click here to download file ‘appendix3.zip’.