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Green Infrastructure and Urban Sustainability: Recent Advances and Future Challenges

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ABSTRACT

Although the majority of urban green infrastructure (GI) programs in the United States, and elsewhere, are being driven by stormwater management challenges arising as a result of the impervious nature of modern cities, GI is also believed to provide other benefits that enhance urban sustainability. This paper discusses the role that GI systems might play in urban climate adaptation strategies for cities like New York City, where increases in both temperature and precipitation are projected over the coming decades. Examples of work conducted by the author and colleagues in New York City to quantify the performance of urban GI are first presented. This work includes monitoring efforts to understand how extensive green roofs retain rainfall, reduce surface temperatures and sequester carbon. Next, a discussion of the advantages that a distributed, or neighborhood level, GI system might bring to a climate adaptation strategy is provided. The paper then concludes with an outline of some of the future work that is needed to fully realize the potential of urban GI systems to address future climate change impacts.

Keywords: Green infrastructure, distributed infrastructure, urban sustainability, stormwater management, climate adaptation

1. INTRODUCTION

The term *green infrastructure* (GI) was coined in 1994 as part of a greenway planning report that advocated for land conservation through a system of greenways, or *green infrastructure*, that were as well-planned and financed as traditional built infrastructure [1]. Since then, the term has been used by planners, designers, scientists, and engineers alike to describe networks of green space, including *natural areas* such as waterways and woodlands, and *built areas* such as parks and community gardens - all of which are widely considered to provide an array of services to humans and the environment [2], [3]. More recently, green infrastructure has gained attention as a means of improving urban stormwater management. This focus has given rise to a class of *engineered green infrastructure*, whose primary design purpose is to reduce urban stormwater runoff and pollution. Examples of *engineered green infrastructure* (GI) include green roofs, porous pavement, rain-gardens and rain cisterns. It is these green infrastructure types that are those most closely associated with GI programs to promote sustainable buildings, neighborhoods and cities. Examples of US cities where large investments in engineered GI are currently underway include Philadelphia ($2.4 billion), New York City ($1.5 billion), Chicago ($50 million), and Cleveland ($42 million) [4]–[6].

Although the majority of urban GI programs in the US, and elsewhere, are being driven by stormwater management challenges arising as a result of the impervious nature of modern cities, GI is also believed to provide other benefits that advance urban sustainability. By increasing vegetation and perviousness within city boundaries, it claimed that GI can help cool urban environments, thus reducing urban heat island impacts [7], trap harmful air-borne particulates [8], sequester greenhouse gases [9], increase and/or restore urban biodiversity [10], improve public health and well-being [11], [12] and even create so-called “green collar jobs” [13], [14]. Thus, many GI programs are promoted not only on the basis of their stormwater management goals, but also on the basis of these claimed co-benefits.

The goal of this paper is to examine some of the advantages and hurdles associated with green infrastructure programs for urban sustainability. The paper will do so by using climate adaptation as an example urban sustainability challenge. In order to focus the paper, New York City (NYC) will be used as a case study. Nonetheless, many of the discussions and conclusions reached in the paper are also relevant to other urban settings, as well as other sustainability challenges.

2. CLIMATE CHANGE IMPACTS

Current climate change projections involve significant uncertainty, not least because scenarios for future green-house gas emissions are unknown. For high emissions scenarios (RCP8.5), mean global temperature rise is projected to be about 4°C (~ 8°F) over the course of the 21st Century, Figure 1, while mean global sea-level rise is projected to be about 2.5 meters (~ 8 feet), Figure 2. Local sea-level and temperature rises are projected to be above or below the mean global levels shown in Figures 1 and 2, depending upon the region under consideration.

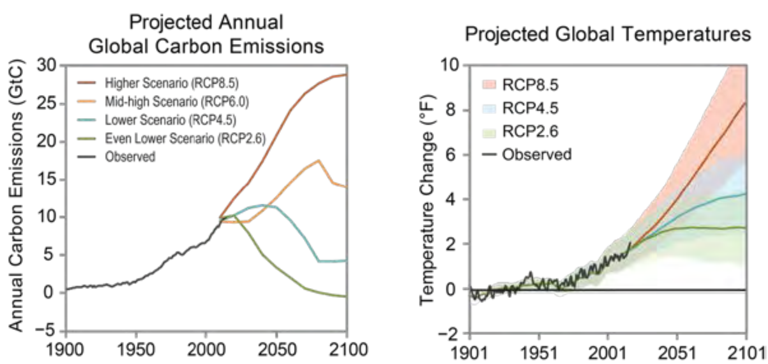

Figure 1. Past and projected changes in global mean temperature rise under different emissions scenarios, from [15].

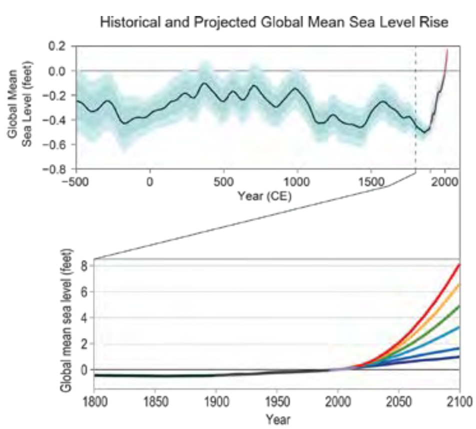

Figure 2. Past and projected changes in global mean sea level rise under different emissions scenarios, from [15].

Nonetheless, despite uncertainties in the projected magnitude of climate change effects, there are general trends that climate scientists and others agree upon. These include a raise in sea-levels; an increase in temperatures; changes in the patterns and amount of precipitation; a decline in snow-cover, permafrost and sea-ice; acidification of the oceans; an increase in the frequency, density and duration of extreme events, and a change in eco-system characteristics. These effects will negatively impact water resources, infrastructure, food supplies and eco-systems, as well as human health and well-being. Given the rapid pace of urbanization, adaptation to climate change impacts is especially important for the world's cities, which are expected to house 66% of the world's population by 2050 [16].

2.1 New York City Temperature and Precipitation Changes

In New York City, historic trends over the past 110 years indicate an increase in both the average temperature and annual precipitation, as recorded at the Central Park Meteorological Station [17]. From a baseline of the year 2000, projected climate change scenarios for a mid-range of emissions scenarios indicate temperature rises of up to 3^{o}C and precipitation increases of up to 11% by the 2050s [18]. These increases will only intensify the present day challenges New York City faces with respect to its stormwater management issues [19] and mitigation of the urban heat island effect [20].

3. NEW YORK CITY GREEN INFRASTRUCUTRE PLAN

In 2010, New York City (NYC) released the NYC Green Infrastructure Plan, which is a multi-decade, multi-billion-dollar plan to improve water quality in the City via the introduction of engineered interventions such as green roofs, right-of-way bioswales, green streets and urban street-trees into NYC's impervious landscape [19], Figure 3. By increasing the amount of vegetation in the City, the NYC Green Infrastructure plan aims to allow precipitation to be soaked up locally, thereby reducing contamination of local water bodies and also incidents of rain induced flooding.

(a) (b)

Figure 3. a) Green roof on a Columbia University building, and b) Right-of-way bioswale in the Bronx, New York City. Image (a) courtesy of Stuart Gaffin, Columbia University. Image (b) courtesy of Nandan Shetty, Columbia University.

3.1 Green Infrastructure Performance Monitoring in New York City

Over the past decade, the author and her colleagues have been researching the performance of green infrastructure in NYC from the vantage point of multiple sustainability metrics [21]–[32], including those relevant to climate adaptation. In the following paragraphs, some example findings are provided for the performance of a common building level GI intervention, namely green roofs.

The two major green roof categories include extensive green roofs, whose substrates are typically 15 cm thick or less and feature short rooting, drought resistant plants such as *sedum*, and intensive green roofs, whose substrates are greater than 15 cm thick and may be sowed with deeper rooting plants including shrubs and trees. Due to their lower cost, reduced maintenance requirements, and lighter weight per unit area, extensive green roofs are more frequently adopted than their intensive counterpart [27]. For this reason, the majority of green roof studies engaging the author and her colleagues involve extensive green roofs. Figure 4 provides the location of three of these extensive green roofs, each of which encompasses a popular construction type. W118 is a Xero Flor America XF301+2FL *vegetated mat system* with a substrate depth of 32 mm, ConEd is a GreenGrid-G2 *modular tray system* with a substrate depth of 100mm, while USPS is a Tecta Green *built-in-place system* with a substrate depth of 100mm. All three roofs are planted with *sedum* species. Monitoring of green roof performance began in 2009 and has been almost continuous since then. Further information on the characteristics of each green roof, monitoring equipment and set-up can be found in [21].

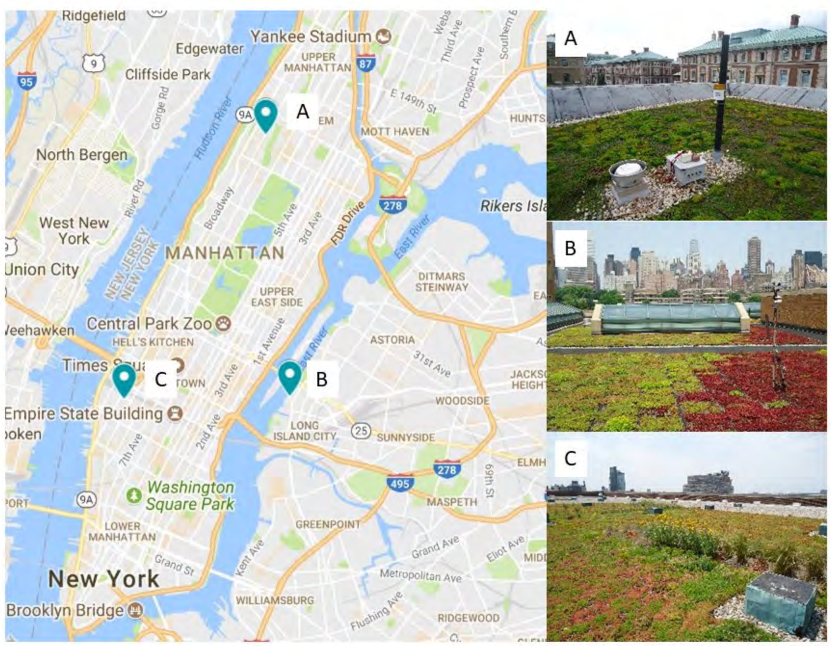

Figure 4. Locations and rooftop views of the W118 (A), ConEd (B) and USPS (C) green roofs, respectively. Map data retrieved from Google Maps (Google Chrome 2018).

Figure 5 summarizes stormwater retention values by storm size category for the three extensive green roof types. As would be expected, green roof rainfall retention reduces with increasing storm depth. Nonetheless, even for largest of storms (50mm +), rainfall retention is

30% or more of incident rainfall. In general, the thinner W118 green roof under-performs with respect to rainfall retention in comparison to the thicker ConEd and USPS systems. Since July 2011, the date when vegetation on all three roofs was considered fully established, the observed annual retention of the W118, ConEd and USPS green roofs has been 45.9%, 50.7% and 56.5%, respectively.

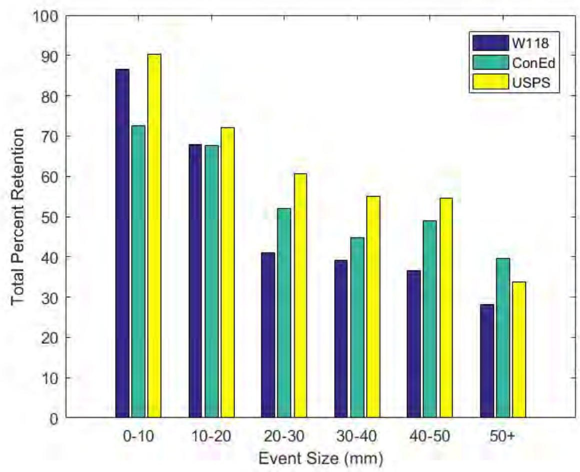

Figure 5. Green roof stormwater retention performance for the W118, ConEd and USPS *sedum* green roofs for different storm event categories.

Green roofs achieve air temperature reductions by transforming adsorbed sunlight into water vapor through evapotranspiration (ET), also termed latent heat loss. White or "cool" roofs, which achieve a high reflection of sunlight, are an alternative to green roofs for air temperature reduction. Temperature data collected over a period of a year from the ConEd green roof and nearby white and black roof treatments, show that white roof and green roof temperatures are actually fairly close, except during summer wet periods when the efficiency of latent heat loss lowers the green roof temperatures significantly below that of the white roof [33]. An illustration of the surface temperature differences that are possible between black, white and green roof areas are shown in Figure 6. It is the observation of large, surface temperatures differences like those shown in Figure 6 (e.g., a different of 46ºC between the black and green roof surfaces) that has spurred interest in the use of vegetated GI to moderate extreme heat in urban spaces.

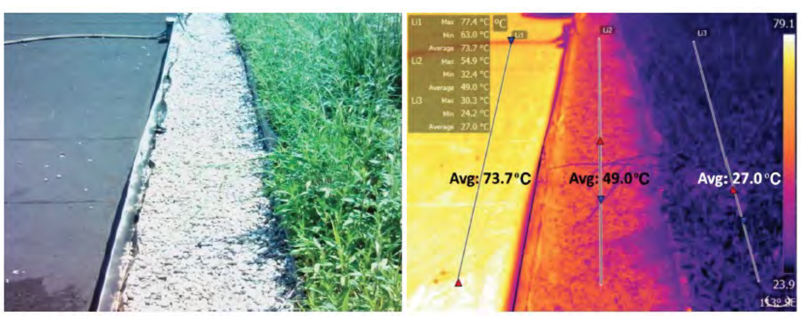

Figure 6. Standard (left) and Infra-red (right) photographs of an NYC based rooftop comprising black, white and green surfaces. Image courtesy of Stuart Gaffin, Columbia University.

Figure 7 provides measurements of diurnal surface-atmospheric CO_2 fluxes for the W118 green roof taken during the month of April. The data show the green roof to be a source of CO_2 during night-time hours (0 – 5am, and 9pm to midnight) and a sink during daylight hours. Overall, the calculated net ecosystem exchange (NEE) of CO_2 for the measurements shown in Figure 7 is -116.5 g CO_2 m^{-2} $month^{-1}$, or -31.8 g C m^{-2} $month^{-1}$. This value is very similar to values reported for an extensive sedum green roof located in Berlin, Germany during the Spring growing season [34]. The authors of [34] report an annual, cumulative NEE of -313 g CO_2 m^{-2} $year^{-1}$, equivalent to -85 g C m^{-2} $year^{-1}$, for the green roof that they studied. For comparison [35] estimate a NEE value of -7.33 kg C m^{-2} $year^{-1}$ associated with carbon storage and sequestration of the NYC urban tree cover, where area refers to the canopy area, which was obtained from aerial photographs taken during a leaf-on state.

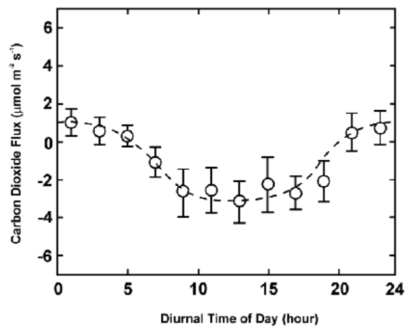

Figure 7. Measured values of CO_2 surface-atmospheric exchange during the Spring growing season for W118.

3.2 Green Infrastructure and Climate Adaptation

Like many other municipal green infrastructure plans, the NYC Green Infrastructure Plan is targeting the construction of thousands of GI interventions, located on both public and private property, to achieve the City's stormwater management goals. The plan is therefore relying on a distributed, or neighborhood scale, infrastructure approach to realize a city-wide objective.

Unlike centralized infrastructure approaches, which usually comprise a smaller number of large investments, distributed infrastructure approaches can be incorporated into urban fabrics at a range of densities and scales. These approaches can thus evolve as performative systems over space and time as needed. Given current uncertainty in climate change projections (see Figures 1 and 2), strategies for climate change adaptation need to be able to change as projections improve over time and/ or impacts are better quantified. Given the flexibility with which a distributed infrastructure system can evolve, the use of distributed infrastructure as part of an urban climate adaptation strategy has many advantages.

Although the NYC Green Infrastructure Plan was not developed as a climate adaptation strategy for NYC, the Plan's promotion of green infrastructure could help mitigate the projected effects of increased precipitation and temperatures in the City, as well as augment local carbon sequestration (refer to Figures 5, 6 and 7). Thus the Plan, inadvertently, encourages a climate adaptation strategy that relies on a distributed infrastructure approach in the face of ill-quantified climate impacts.

4. CHALLENGES AND FUTURE NEEDS

As discussed above, distributed GI appears to have promise as a strategy for climate change adaptation in urban environments. Nonetheless, as discussed below, there are still hurdles that need to be overcome in order to fully realize the actual potential of this promise.

Despite significant progress in documenting the performance of an individual GI intervention, an understanding of how thousands of GI interventions perform as a system of interventions remains lacking. Developing this understanding is essential to advancing system level optimization of multi-component GI schemes for climate adaptation, or other urban sustainability goals. Modeling approaches might be one way to make the necessary progress. However, even in the well-studied area of stormwater management, process-based predictive models have had limited success in forecasting the behavior of an individual GI installation [23], let alone a multi-component GI system. One reason for this, is poor parameterization of evapotranspiration processes for engineered GI. An alternative to systems level modeling is systems level monitoring. This approach has the advantage of providing direct, possibly real-time, information on neighborhood or city-wide GI performance. Furthermore, with enough data collection, it might be possible to create data driven models to inform future system design, optimization and operation strategies. Nonetheless, advancement of this approach will require the development of appropriate sensor networks as well as accompanying data-management and support systems: In other words, a "smart-cities' type approach to urban GI programs.

Improved understanding of the role of engineered GI in mitigating urban heat island effects is also needed. While it is true that large patches of greenery, such as NYC's Central Park, have measureable effects on air temperatures within the park boundary, the cooling effects exerted by smaller areas, such as the green roofs or right-of-way bio-swales shown in Figure 3, are less clear. Thus, more research is needed to define the scale and spatial patterns of urban vegetation required to significantly lower air temperatures in dense urban environments like NYC.

Different from larger-scale climate adaptation strategies, such as the installation of massive underground stormwater storage tanks, distributed GI systems are not only comprised of many more elements, they are also more likely to interface with urban social systems and communities. This can add complex facets of public acceptance and stewardship to the equation of GI performance, which are not always accounted for in GI design, siting and maintenance. Public acceptance and stewardship lessons learned to date from NYC's Green Infrastructure program indicate the importance of greater public dialogue regarding infrastructure placement in the public right-of-way (e.g. Figure 3b). In general, public acceptance of right-of-way GI in NYC has been mixed, with many residents not embracing this vegetative intervention due to concerns about loss of parking, accumulation of trash in the GI, dislike of GI plant palettes – especially native grasses, and general dis-satisfaction about perceived lack of public consultation prior to implementation. In some instances, right-of-way GI has been vandalized in ways that actually compromise its physical performance. Survey work by the author and colleagues indicate that the public places more value on the cultural, social and aesthetic services provided by GI, than the environmental services. Thus, GI designs that account for public value systems, might have better long-term performance and stewardship outcomes than present-day designs.

Currently, efforts to design GI to maximize performance beyond stormwater management remain limited. For example, [34] note that carbon uptake by the sedum green roof they monitored in Berlin, Germany declined when substrate moisture content fell below 0.05 m^3m^{-3}, while [33] observed that high substrate moisture contents were linked to lower green roof temperatures. Yet, the active management of substrate moisture content to enable optimal rainfall capture, carbon uptake and the lowering of surface temperatures is neither a design nor operational feature of most extensive green roofs. Going forward, more attention needs to be paid to the design and operation of GI interventions that maximize as many sustainability benefits as possible.

Finally, questions still remain as to how to define "acceptable" performance for a distributed GI system, whether for the purpose of climate adaptation or not. For example, with respect to performance redundancy, questions remain as to what is an acceptable factor of safety for a distributed system? And should a factor of safety be applied to each individual component of a GI system (i.e, each component has a built-in factor of safety) or the entire system itself (i.e., the system has redundant components)? In addition, there are questions regarding system resiliency. For example, are distributed systems more resilient because they are comprised of very, many components (so if several components fail the overall system performance is not compromised) or are they less resilient because it is hard to manage and secure a system of very many components? Furthermore, with respect to funding, what is the model for financing distributed GI systems that are installed on private land to perform public good? These, and other, questions will need answers if distributed GI systems are to become viable elements of urban climate adaptation strategies.

5. CONCLUSIONS

Distributed, or neighborhood level, systems of green infrastructure can contribute to urban sustainability goals in multiple ways. This paper discussed climate adaptation as one such example. Because GI can be incorporated into urban fabrics at a range of densities and scales, the performance of GI systems can evolve over space and time as needed. Given current uncertainty in climate change projections and impacts, the flexibility of an adaptation strategy whose performance can continually evolve has many advantages. Nevertheless, there are a number of challenges that need to be overcome to advance the use of GI for climate adaptation.

Despite the fact that significant progress has been made in documenting the performance capacity of individual GI interventions, an understanding of how thousands of GI interventions perform as a system remains lacking. Developing this understanding is essential to designing multi-component GI interventions for climate adaptation, or other urban sustainability goals. In addition, better understanding of the scale and patterns of urban vegetation required to mitigate urban heat island effects is needed, as are new designs for GI that optimize different performance attributes and improve public acceptability and stewardship outcomes for GI sited in the public-right-of way. Finally, fundamental questions regarding what defines acceptable performance for a distributed GI system still need to be addressed.

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REFERENCES

[1] Florida Greenways Commission, "Creating a statewide Greenways system, for people... for wildlife... for Florida.," Tallahassee, 1994.

[2] M. a Benedict and E. T. McMahon, "Green Infrastructure: Smart Conservation for the 21st Century," *Renew. Resour. J.*, pp. 12–19, 2002.

[3] J. P. Newell *et al.*, "Green Alley Programs: Planning for a sustainable urban

infrastructure?," *Cities*, vol. 31, pp. 144–155, 2013.
[4] City of Chicago, "2014 Budget Overview," Chicago, IL, 2014.
[5] NEORSD (Northest Ohio Regional Sewer District), "Green Infrastructure Plan," 2012.
[6] Philadelphia Water Department, "Green City Clean Waters," Philadelphia, 2011.
[7] E. Oberndorfer *et al.*, "Green Roofs as Urban Ecosystems: Ecological Structures, Functions, and Services," *Bioscience*, vol. 57, no. 10, pp. 823–833, 2007.
[8] J. Yang, Q. Yu, and P. Gong, "Quantifying air pollution removal by green roofs in Chicago," *Atmos. Environ.*, vol. 42, pp. 7266–7273, Oct. 2008.
[9] K. L. Getter, D. B. Rowe, G. P. Robertson, B. M. Cregg, and J. A. Andresen, "Carbon sequestration potential of extensive green roofs.," *Environ. Sci. Technol.*, vol. 43, no. 19, pp. 7564–7570, Oct. 2009.
[10] Toronto and Region Conservation Authority, "Evaluation of an Extensive Greenroof," TORONTO, ONTARIO, 2006.
[11] H. Niu, C. Clark, J. Zhou, and P. Adriaens, "Scaling of economic benefits from green roof implementation in Washington, DC," *Environ. Sci. Technol.*, vol. 44, no. 11, pp. 4302–4308, Jun. 2010.
[12] T. Van Renterghem and D. Botteldooren, "In-situ measurements of sound propagating over extensive green roofs," *Build. Environ.*, vol. 46, pp. 729–738, Mar. 2011.
[13] Center for American Progress, "New York City Green Collar Jobs Roadmap," 2009.
[14] The New York Times, "Millions of Jobs of a Different Collar," *Online*. 2008.
[15] D. J. Wuebbles, D. W. Fahey, K. A. Hibbard, D. J. Dokken, B. C. Stewart, and T. K. Maycock, "Climate science special report: fourth National Climate Assessment," *U.S. Glob. Chang. Res. Progr.*, vol. 1, p. 470, 2017.
[16] United Nations, "World Urbanization Prospects 2014," 2014.
[17] J. E. Rosenthal, K. M. Knowlton, C. Rosenzweig, R. Goldberg, and P. L. Kinney, "One Hundred Years of New York City's 'Urban Heat Island': Temperature Trends and Public Health Impacts," in *American Geophysical Union, Fall Meeting*, 2003.
[18] "New york city panel on climate change 2015 report executive summary," *Annals of the New York Academy of Sciences*, vol. 1336, no. 1. pp. 9–17, 2015.
[19] NYC DEP, "NYC Green Insfrastructure Plan: A sustainable strategy for clean waterways," New York, NY, 2010.
[20] S. R. Gaffin *et al.*, "Bright is the new blackmulti-year performance of high-albedo roofs in an urban climate," *Environ. Res. Lett.*, vol. 7, no. 1, 2012.
[21] T. B. Carson, D. E. Marasco, P. J. Culligan, and W. R. McGillis, "Hydrological performance of extensive green roofs in New York City: Observations and multi-year modeling of three full-scale systems," *Environ. Res. Lett.*, vol. 8, no. 2, 2013.
[22] P. Culligan *et al.*, "Evaluation of Green Roof Water Quantity and Quality Performance in an Urban Climate," 2014.
[23] T. Carson, M. Keeley, D. E. Marasco, W. McGillis, and P. Culligan, "Assessing methods for predicting green roof rainfall capture: A comparison between full-scale observations and four hydrologic models," *Urban Water J.*, vol. 14, no. 6, 2017.
[24] D. E. Marasco, B. N. Hunter, P. J. Culligan, S. R. Gaffin, and W. R. McGillis, "Quantifying evapotranspiration from urban green roofs: A comparison of chamber measurements with commonly used predictive methods," *Environ. Sci. Technol.*, vol. 48, no. 17, pp. 10273–10281, 2014.
[25] D. E. Marasco, P. J. Culligan, and W. R. McGillis, "Evaluation of common evapotranspiration models based on measurements from two extensive green roofs in New

York City," *Ecol. Eng.*, vol. 84, 2015.
[26] R. Hakimdavar, P. J. Culligan, M. Finazzi, S. Barontini, and R. Ranzi, "Scale dynamics of extensive green roofs: Quantifying the effect of drainage area and rainfall characteristics on observed and modeled green roof hydrologic performance," *Ecol. Eng.*, vol. 73, 2014.
[27] R. Hakimdavar, P. J. Culligan, A. Guido, and W. R. McGillis, "The Soil Water Apportioning Method (SWAM): An approach for long-term, low-cost monitoring of green roof hydrologic performance," *Ecol. Eng.*, vol. 93, pp. 207–220, 2016.
[28] R. M. Elliott, R. A. Gibson, T. B. Carson, D. E. Marasco, P. J. Culligan, and W. R. McGillis, "Green roof seasonal variation: Comparison of the hydrologic behavior of a thick and a thin extensive system in New York City," *Environ. Res. Lett.*, vol. 11, no. 7, 2016.
[29] R. M. Elliott, E. R. Adkins, P. J. Culligan, and M. I. Palmer, "Stormwater infiltration capacity of street tree pits: Quantifying the influence of different design and management strategies in New York City," *Ecol. Eng.*, vol. 111, 2018.
[30] N. Shetty, P. J. Culligan, B. Mailloux, W. R. McGillis, and H. Y. Do, "Bioretention Infrastructure to Manage the Nutrient Runoff from Coastal Cities," in *Geotechnical Special Publication*, 2016, vol. 2016–Janua, no. 273 GSP.
[31] D. Roman, A. Braga, N. Shetty, and P. Culligan, "Design and modeling of an adaptively controlled rainwater harvesting system," *Water (Switzerland)*, vol. 9, no. 12, 2017.
[32] L. J. Whittinghill, D. Hsueh, P. Culligan, and R. Plunz, "Stormwater performance of a full scale rooftop farm: Runoff water quality," *Ecol. Eng.*, vol. 91, 2016.
[33] S. R. Gaffin, C. Rosenzweig, J. Eichenbaum-Pikser, R. Khanbilvardi, and T. Susca, "A Temperature and Seasonal Energy Analysis of Green, White, and Black Roofs," *Water Resour.*, p. 19, 2010.
[34] J. Heusinger and S. Weber, "Extensive green roof CO2 exchange and its seasonal variation quantified by eddy covariance measurements," *Sci. Total Environ.*, vol. 607–608, pp. 623–632, 2017.
[35] D. J. Nowak, E. J. Greenfield, R. E. Hoehn, and E. Lapoint, "Carbon storage and sequestration by trees in urban and community areas of the United States," *Environ. Pollut.*, vol. 178, pp. 229–236, 2013.