Greening From the Rooftops

Visualizing the Future Potential of Green Roofs in New York City

Nour Zein

M.S. Data Visualization, Parsons School of Design

M.S. Environmental Policy, The New School

B.S. Honours Biology, McGill University

Supervisor

Daniel Sauter

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Contents

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1. Abstract

As the climate continues to warm, and extreme weather events are more frequent and stronger, New York City must adapt to these changes to maintain the health and well-being of its population. Green roofs are a way to do so; they provide environmental benefits such as surface temperature mitigation, stormwater management, and biodiversity conservation that improve the resiliency and adaptive capacity of the city. However, even though the benefits of green roofs have been greatly studied, and a need to implement them on a widescale in cities is inarguable, only 0.1% of NYC’s 1 million rooftops have green roofs. Greening From the Rooftops was developed to transform the scientific literature on green roofs into a tool that the average person and decision maker can use. It visualizes and maps potential rooftops for implementing green roofs, and calculates the environmental benefits the potential green roof would bring if installed.

2. Introduction

Cities are increasingly responsible for the health and well-being of the majority of the human population. It is projected that by 2050, 66% of the world's population will be urban, an increase in both relative and absolute numbers of urban population.[1] However, cities are the most vulnerable places for the impacts of climate change. This is because not only do they hold the majority of the world's population, they are also by design ill equipped to handle the rapidly changing climates projected for the future. Before urbanization and the disruption of natural habitats, soil and vegetation were integral parts of a healthy ecosystem that managed solar energy, precipitation, and nutrient cycles for the propagation of life on Earth. In these natural habitats, rainwater infiltrates into the soil to be converted to energy by plants, or gets evaporated back into the atmosphere to be used as rainwater again. This process, called evapotranspiration functions as a cooling system that effectively reduces high levels of potentially detrimental solar stress on the earth's surface .[2] However as a consequence of urbanization , soil and vegetation is replaced by impervious surfaces in the form of buildings, roofs, roads, and parking lots. Since these surfaces do not absorb water, they produce a huge amount of storm water runoff that will only continue to increase due to the extreme weather events of climate change.[3] Storm water runoff carries pollutants into the sewers and exceeds channel capacities causing combined sewer overflow events (CSO) and in some cases flooding.[4] In addition to this pollution of the waterways, the cooling benefit of evapotranspiration is no longer happening, a dangerous consequence to our increasing warming world. These concerns show the importance of recovering green space in our cities. Designing greener and healthier cities needs to be a priority in order to insure the adaptive and resilient capacity of our cities.

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[1] World Cities Report (2016): Urbanization and Development. (2016). Retrieved from https://unhabitat.org/books/world-cities-report/

[2] *Evapotranspiration : Principles and applications for water management* (2014). Oakville, ON : Apple Academic Press, Inc.

[3] USGS. Impervious Surfaces and Flooding. Retrived from https://www.usgs.gov/special-topic/water-science-school/science/impervious-surfaces-and-flooding?qt-science_center_objects=0#qt-science_center_objects

[4] EPA. Sources and Solutions: Stormwater. Retrieved from https://www.epa.gov/nutrientpollution/sources-and-solutions-stormwater

Green infrastructure present solutions to cities' most challenging problems. Green roofs are an inexpensive solution to outdated sewer infrastructure and extreme temperature regulation. Green roofs involve growing vegetation on rooftop surfaces, predominantly using soil, a water retention filter, and a drainage layer.[5] Their greatest power comes from the fact that they cover impervious roof surfaces with permeable, living, breathing plant material. Because they cover the impervious surface, they act like an insulation that regulates building temperature, effectively reducing energy consumption on heating in the winter and air conditioning in the summer.[6] They are also effective at reducing the surrounding temperature directly and through the reduced energy consumption.[7] Green roofs can also help mitigate storm water runoffs by retaining precipitation and reducing the flow into sewer systems.[8] Another benefit that has a less direct but still large scale effect is that it provides habitat for wildlife.[9]

Although the benefits of green roofs have been greatly studied, and a need to implement them on a widescale in cities is inarguable, tools that help identify viable buildings and visualize the benefits in those areas have not been developed. In this project, I aim to develop a tool that will visualize the future potential of green roofs in an explorative and interactive way, while calculating the benefits of their implementation. The goal is to transform scientific literature of the benefits and building suitability analysis into a tool that the average person and hopefully decision makers can use to identify and explore areas from the city all the way down to the building level.

The application will include four main sections: 1) at the top, a map filter of building attributes relevant to the legality of the implementation of green roofs; 2) the summary of the potential of the city, each borough, and map region; 3) a dynamic benefits calculator for heat, stormwater

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[5] Refahi, A. H., & Talkhabi, H. (2015). *Investigating the effective factors on the reduction of energy consumption in residential buildings with green roofs*doi:https://doi.org/10.1016/j.renene.2015.02.030

[6] Del Barrio EP. (1998.) Analysis of the green roofs cooling potential in buildings. Energy and Buildings 27: 179–193.

[7] Getter KL, Rowe DB. (2006.) The role of green roofs in sustainable develop- ment. HortScience 41: 1276–1286

[8] Viola, F., Hellies, M., & Deidda, R. (2017). Retention performance of green roofs in representative climates worldwide. *Journal of Hydrology, 553*, 763. doi:10.1016/j.jhydrol.2017.08.033

[9] Braaker, S., Ghazoul, J., Obrist, M. K., & Moretti, M. (2014). Habitat connectivity shapes urban arthropod communities: The key role of green roofs. *Ecology, 95*(4), 1010-1021. doi:10.1890/13-0705.1

runoff, and habitat that will be based on the map region within view; 4) and finally the map that will show the distribution of current and potential green roofs.

I hope to create a controlled environment where the average person can learn about potential green roofs and their distribution in the city, while a more intentional user can explore the potential and benefits not just of the city or borough, but of a specific location or type of building relevant to their objective. I will focus on New York City due to its high building density and available rooftop space. My goal is to facilitate the implementation of green roofs to improve the resiliency and adaptive capacity of New York City. In the thesis, I will start by providing background on green roofs: the discovery of green roofs, the evolution of the technology and its sophistication, and finally the ecological and economic impacts they provide. The objective is to understand green roof systems and their necessity for sustainable city design. Finally, I will address the methodology of my data visualization: the data used, the design motivation, and the development process.

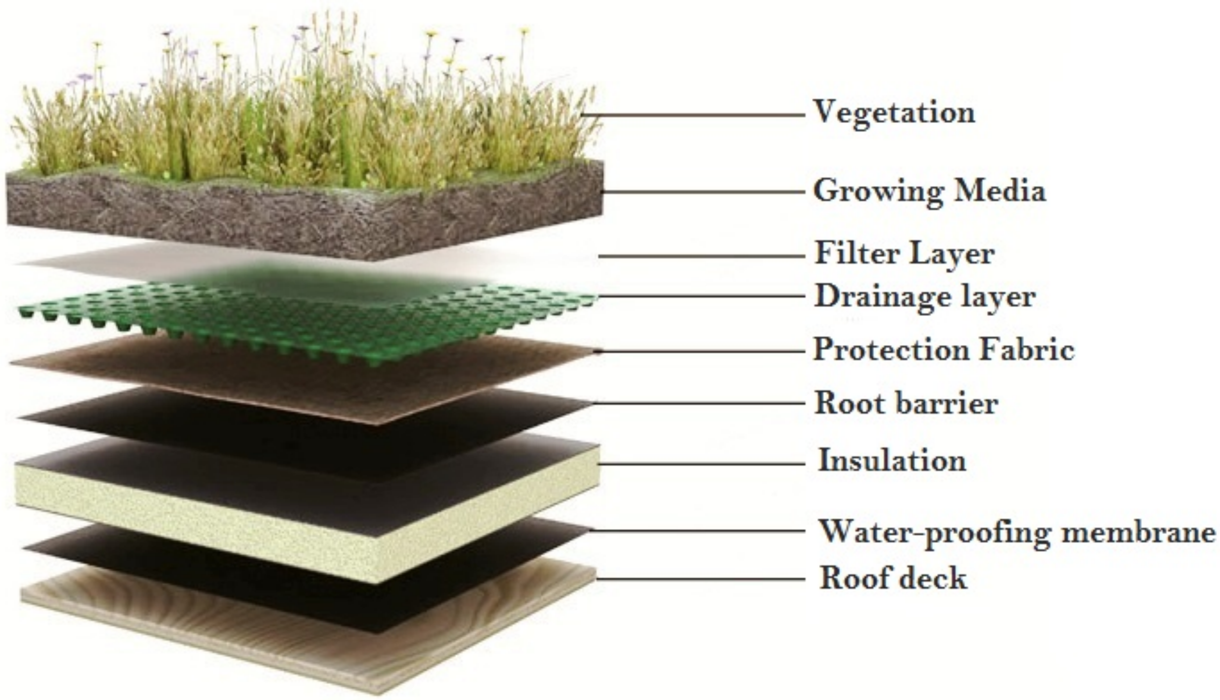
3. Treatment

What are Green Roofs and Where do They Come From

From the Hanging Gardens of Babylon to the Viking Longhouses

In order to understand the importance of green roofs, we must dive into the history of how this technology was discovered. Not to be confused with the rooftop garden which is potted plants on a roof, green roofs also known as *vegetated roofs* or *living roofs* or *sod roofs* are established plant material on flat or slightly sloped rooftops. At the most basic, they are composed of a vegetation layer, soil layer, and waterproofing/drainage layer.[10]

[10] Green Roof Design: NYC: United States: Green Roofs NYC. (2018). *Greenroofsnyc.com*, www.greenroofsnyc.com/landscape-design.



They are not a new technology and have been around for thousands of years. The most famous historical green roof is the Hanging Garden of Babylon from the 7th century.[11] Designed by King Nebuchadnezzar for his wife who missed the flora from her home, the green roof which was composed of reeds and tarplants made primarily for aesthetic purposes. The inspiration for contemporary benefit-based green roofs comes from Scandinavia during the middle ages.[12] In those harsh cold climates, sod or *turf* roofs where put on top of several water-retaining membranes made of birch bark. They came in a lot of different varieties, bright green and grassy, sometimes golden yellow as if made from wheat. A few had flowers mixed in and even small trees. The soil acted helped retain heat, while the vegetation was used to keep the soil from eroding. The Viking longhouses were fitted with them to create resilient structures they knew would survive the aggressive winter conditions and insulate the inside from the cold.[13] The Faroe Islands, home to the largest collection of green roofs in the world are maintained from the Viking settlers. They are a pragmatic and effective solution to the extreme rainy and wet environmental conditions of the area. This is because, as will be elaborated on later, green roofs act like a

[11] Osmundson, T. (1999). Roof gardens: History, design and construction. W.W. Norton & Company, New York.

[12] ibid
[13] ibid

protective layer to rooftop membranes. They are also effective at absorbing precipitation. Until this day, Scandinavia still widely implements green roofs; in fact every year an award is given to the best green roof project in Scandinavia by the board of the Scandinavian Green Roof Association. For them, green roofs have always been a clever, inexpensive (in energy use and cost), and effective way to adapt to the extreme weather conditions that kind of climate goes through. However, green roofs during this time had still not been recognized by the larger discussion of city design and architecture.

The Emergence of Contemporary Green Roofs

Contemporary green roof technology as we know it today was first formally introduced back in the 1970s in Germany, when two landscape architects, Gerda Gollwitzer and Werner Wirsing, published a comprehensive book titled *Roof Areas Inhabited, Viable, and Covered by Vegetation* outlining the basic principles of modern green roofs.[14] In 1975, the Landscape Research, development and Construction Society was founded, and soon after the widely followed green-roof standards.[15] This development of industry standard codes would not have been possible without the trial and error, repeated experimentation with materials, and time investment that took place during this time to establish green roofs as a viable technology that is feasible to implement. With an evolution in the technology that followed the years after, green roofs were widely accepted in Europe in the 1980s.[16] Green roofs finally got the attention of North America at the end of the twentieth century, and the most notable sign of that is when the U.S Green Building Council creates the LEED rating system and awards green roofs up to 6 points in a 69-point system.[17] With their importance being recognized, the science and design behind this technology was becoming well understood and documented.

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[14] Kohler, M., and Keeley, M. (2005). Berlin: Green roof technology and development, p. 108–112. In Earth Pledge. Green roofs: Ecological design and construction. Schiffer Books, Atglen, Pa.
[15] Jim, C. Y. (2017). *Green roof evolution through exemplars: Germinal prototypes to modern variants* doi:https://doi-org.libproxy.newschool.edu/10.1016/j.scs.2017.08.001

[16] ibid
[17] U.S. Green Building Council. LEED v4.1. (n.d.). Retrieved from https://www.usgbc.org/leed/v41?creative=340482139151&keyword=leed building standards&matchtype=b&network=g&device=c&gclid=EAIaIQobChMI_IuX572i6AIVEIiGCh20jQ6REAAYASAAEgLOqvD_BwE#bdc

Types of Green Roofs

Modern green roofs can be categorized into two main categories depending on their maintenance needs: Intensive and extensive green roofs. In addition to maintenance needs, purpose of green roof and building suitability and load baring capacity need be taken into account when determining whether an intensive or extensive green roof should be considered. Their differences will be outlined in the next paragraphs.

Intensive Green Roofs

Intensive green roofs get their name from the "intense" maintenance they require. They require a thicker layer of growing medium, usually greater than 6 inches, where a variety of plants can be planted for many different purposes. They are heavier on the roof, usually greater than 150 pounds per square foot, so additional structural support is needed and a roof with a high load bearing capacity.[18] For these reasons they require a flat like surface. These green roofs support a wide range of plants including trees, flowering shrubs, and vegetables. They tend to be designed to create a park-like or garden-like setting and can be used for urban agriculture purpose and recreational reasons. Since they are usually composed of large plants, a lot of which are non-native for aesthetic and recreational purposes, they require proper irrigation systems and frequent fertilization, compared to extensive green roofs that do not need either.[19] Additionally, because they are frequently built to be occupied, they not only need maintenance for their vegetation, but also for the common spaces such as walkways and benches that tend to be installed in these areas. For these reasons, they offer a wider range of benefits of the two green roofs, but are the more expensive and need more requirements.

Extensive Green Roofs

Extensive green roofs are the low maintenance type of green roofs. This means that they require little to no fertilization, irrigation, trimming, or any care taking of the sorts and rely solely on the

[18] Johnston, J., Newton, J. (1993). Building Green: A Guide to Using Plants on Roofs, Walls and Pavements. The London Ecology Unit, London.
[19] ibid

environmental conditions to survive. For this reason, plants need to be chosen correctly for the climate conditions. They are typically not accessible to the public and might not even be visible. They are shallow in depth, around 3-6 inches deep usually and lightweight, between 15-50 pounds per square foot.[20] Because of the shallow depth of the structure, they are usually planted in a tray or mat like system to make the structure resilient to extreme conditions like harsh wind and storms.[21] Additionally, because of the shallow soil depth and little to no maintenance, plant material is limited to versatile species such as herbs, grasses, mosses, and other drought-tolerant succulents such as Sedum. Sedum is the a popular type of plant used in extensive green roofs.[22] This is because they demonstrate the most drought-resilient capabilities.[23][24][25] They also have shallow roots that allows them to survive in shallow soil. They also require little to no nutrients, and have the ability to retain water making them heat and drought tolerant. Finally, they can grow on flat or sloped roofs, they are evergreen- meaning they remain green year round- and they are easy to propagate, making them commercially viable and the cheapest to use.[26] Since extensive green roofs that are predominantly made of sedum are extremely easy to implement and have a wide range of benefits (I will go into this later), in this study I will focus my analysis of future potential of extensive- predominantly sedum green roofs. This is a summary table of the differences:

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[20] Johnston, J., Newton, J. (1993). Building Green: A Guide to Using Plants on Roofs, Walls and Pavements. The London Ecology Unit, London.

[21] ibid

[22] Dunnett, N., Kingsbury, N. (2008). Planting Green Roofs and Living Walls, 2nd edition. Timber Press, Portland Oregon.

[23] Nagase, A., & Dunnett, N. (2010). *Drought tolerance in different vegetation types for extensive green roofs: Effects of watering and diversity* doi: https://doi.org/10.1016/j.landurbplan.2010.07.005

[24] Gurevitch, J., Teeri, J.A., Wood, A.M. (1986). Differentiation among populations of Sedum wrightii (Crassulaceae) in response to limited water availability: water relations, CO_2 assimilation, growth and survivorship. Oecologia 70, 198–204.

[25] Iijima, K. (2001). A study on discover the growth characteristics of Sedum as an urban landscape plant. J. Jpn. Inst. Landscape. Architect. Extra Issue 5, 53–84.

[26] Sedum and a Sedum roof. (n.d.). Retrieved from https://www.sempergreen.com/us/solutions/green-roofs/everything-about-sedum

Attribute	Intensive	Extensive
Vegetation Type	Wide range including trees, flowering shrubs, and vegetables	Sedum, succulents, herbs, grasses, and mosses
Thickness/Depth	> 6 inches	3- 6 inches
Weight	> 150 pounds per square footage	15-50 pounds per square footage
Maintenance	Same as regular garden	Rare if at all
Walking space	Yes	None/Limited
Inclination	Mostly flat	Up to 45 degrees
Irrigation	Always required	Mostly without
Load bearing capacity	Requires strong roof capacity	Usually suffecient

Whether intensive or extensive, green roofs provide cities with a series of benefits regardless of their maintenance level.

Benefits of Green Roofs

Green roofs are extremely beneficial in a lot of different ways to a lot of different people/animals/things. I will focus on four main ones that the most relevant to the NYC. Those benefits include storm water management, heat mitigation, energy consumption reduction, and habitat for biodiversity. Other benefits are the capacity for urban agriculture and food security, community space, improved mental health, improved air quality, economic stimulation, and rooftop membrane protection and longevity.

Storm Water Management

One of the most important benefit that green roofs provide is storm water management. Green roofs can help reduce the total amount of storm water runoff because unlike impervious surfaces, the soil can absorb the precipitation that will later be evaporated from the surface back into the atmosphere or released in the form of transpiration- water vapor being released from the plant or leaf.[27] A study done by Kolb (2004) found that green roofs can reduce storm water runoff this way by 45%. He found that a significant determining factor for green roof absorption capacity was medium type. Other factors include depth and plant species. Depending on the type of green roof system, anywhere from 60% to 100% can be reduced.[28][29][30] One study found that the mean retention capacity was close to 82.5 to 85.7%.[31] Another study should that if Toronto used 6% of its roof area for green roofs, the city could retain the same amount of storm water as a 60 million dollar storage tunnel.[32] These studies demonstrate how effective green roofs are at reducing total volumes of storm water runoff, which is a concern in a city like New York with its old sewer infrastructure and Combined Sewer Overflows (CSOs) that dump water and sewage into the waterways during high precipitation events, that will only increase with climate change.

Another way that green roofs can help mitigate storm water is by slowing down the runoff rate. This is because even though green roofs retain water, the soil eventually becomes saturated. When that happens, water begins to drain, and that process is how the runoff rate is slow. Studies have found that the delay can be anywhere between 95 minutes to 4 hours, compared to non-

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[27] Kolb, W. (2004). Good reasons for roof planting: Green roofs and rainwater. Acta Hortic. 643:295–300.
[28] DeNardo, J.C., Jarrett, A.R., Manbeck, H.B. , Beattie, D.J., and Berghage, R.D. (2005). Stormwater mitigation and surface temperature reduction by green roofs. Trans. ASAE 48:1491–1496.
[29] Moran, A., Hunt, B., and Jennings, G. (2004). A North Carolina field study to evaluate green roof runoff quantity, runoff quality, and plant growth, p. 446–460. In Proc. of 2nd North American Green Roof Conference: Greening rooftops for sustainable communities, Portland, OR. 2–4 June 2004. The Cardinal Group, Toronto.
[30] Rowe, D.B., Rugh, C.L., VanWoert, N., Monterusso, M.A., and Russell, D.K. (2003). Green roof slope, substrate depth, and vegetation influence runoff, p. 354–362. In Proc. of 1st North American Green Roof Conference: Greening rooftops for sustainable communities, Chicago. 29–30 May 2003. The Cardinal Group, Toronto.

[31] Burszta-Adamiak, E. (2012). Analysis of the retention capacity of green roofs. *Journal of Water and Land Development, 16*(1), 3. doi:http://dx.doi.org.libproxy.newschool.edu/10.2478/v10025-012-0018-8.

[32] Peck, S.W. (2005). Toronto: A model for North American infrastructure development, p. 127– 129. In EarthPledge. Green roofs: Ecological design and construction. Schiffer Books, Atglen, Pa.

green impervious roofs.[33] A study in North Carolina found that green roofs had run off reduction rates from 57% to 87%.[34] This delay is really valuable because the big issue with storm water, especially in a city like New York, is when it exceeds the capacity of the sewer system, the systems overflows causes CSO events- which is when the water from runoff and the sewer both get dumped into the surrounding waterways. CSO events create public health issues and environmental degradation.[35] For this reason, controlling the rate of the runoff going into the pipes and reducing the total volume of runoffs can have a huge positive impact on a city.

Temperature Mitigation and Energy Consumption

The urban heat island effect is when a metropolitan area is much warmer than the surrounding suburban and rural areas. This is because urbanized areas have fewer vegetation, are covered by construction materials with higher albedos and heat absorbing capacities, and are more energy consuming which gives off more heat. Roads, parking lots, and rooftops made from asphalt and concrete end up soaking up the sun's radiation during the day and release it as heat into the surrounding air at night.[36] According to the United States Environmental Protection Agency (EPA), "The annual mean air temperature of a city with 1 million people or more can be 1.8-5.4°F (1-3°C) warmer than its surroundings. In the evening, the difference can be as high as 22°F (12°C)."[37] The heat island effect contributes to an increase in energy demand, especially during a heat wave, which further contributes to the effect. It also causes an increase in air conditioning costs, air pollution and greenhouse gas emissions, water pollution, and finally heat-related illness and mortality.[38] These effects will only worsen with global warming, in a negative feedback loop. Cities need to be designed differently to address this fundamentally urban problem. Green

[33] Liu, K. (2003). Engineering performance of rooftop gardens through field evaluation. Proc. of the 18th International Convention of the Roof Consultants Institute. 93–103.

[34] Moran, A., Hunt, B., and Smith, J. (2005). Hydrologic and water quality performance from green roofs in Goldsboro and Raleigh, North Carolina, p. 512–525. In Proc. of 3rd North Amer- ican Green Roof Conference: Greening rooftops for sustainable communities, Wash- ington, DC. 4–6 May 2005. The Cardinal Group, Toronto.

[35] Laughlin, J. (2012). EPA regional focus: Nutrient pollution, CSO/SSOs are top issues for region 7. *Waterworld, 28*(2), 27

[36] Oke, T. R. (1982). The energetic basis of the urban heat island. *Quarterly Journal of the Royal Meteorological Society, 108*(455), 1-24. doi:10.1002/qj.49710845502

[37] Environmental Protection Agency. Heat Islands. https://www.epa.gov/heat-islands

[38] ibid

roofs are an economically sound and effective solution to the heat island effect because they contribute to surface temperature reduction which in turn contributes to lower ambient air temperatures. This is because vegetation does not absorb heat the way construction material does; it converts it into energy for the plant. One study found that green roofs were effective at reducing surface heat temperatures anywhere from 57% to 63%.[39] Several other studies using a wide range of green roofs also demonstrated that green roofs show a significant reduction in surface temperature in the summer, a limited temperature fluctuation of the surface compared to barren roofs, and an insulating effect that limited heat dispersion in the winter.[40][41][42][43] All of these effects are connected to the nature of a green roof- they act as a non-heat absorbing insulating layer to buildings that effectively regulate the interior air temperature as well as the exterior surface temperature. This insulating effect, in addition to having health benefits on people, has been found to help prolong the roof membrane of a building.[44] Additionally, with temperature regulation being done "naturally", energy consumption would only go down because people would not need to use as much heating and cooling. Buildings have been shown to contribute to 36% of all energy consumption and 65% of total electricity consumption. Asking any person who lives in NYC where their electricity consumption primarily comes from, they will tell you heating and cooling. Wide scale green roof implementation can greatly impact energy savings.[45]

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[39] Bevilacqua, P., Mazzeo, D., Bruno, R., & Arcuri, N. (2017). *Surface temperature analysis of an extensive green roof for the mitigation of urban heat island in southern mediterranean climate* doi:https://doi-org.libproxy.newschool.edu/10.1016/j.enbuild.2017.05.081

[40] K. Liu, J. Minor, Performance Evaluation of an Extensive Green Roof, GreeningRooftops for Sustainable Communities, Washington, D.C, 2005, pp. 1–11.

[41] Julià Coma, Gabriel Pérez, Cristian Solé, Albert Castell, Luisa F. Cabeza. (2016) . Thermal assessment of extensive green roofs as passive tool for energy, Renew. Energ. 85 106–1115, http://dx.doi.org/10.1016/j.renene.2015.07.074.

[42] Theodosiou, T., Aravantinos, D., Tsikaloudaki, K. (2014). Thermal behavior of a green vs. a conventional roof under Mediterranean climate conditions, Int. J. Sustainable Energy 33 (1) 227–241, http://dx.doi.org/10.1080/14786451.2013.772616.

[43] Kristin L. Getter, Bradley Rowe, D., Jeff Andresen, A., Indrek, S. (2011) Seasonal heat flux properties of an extensive green roof in a Midwestern U.S. climate, Energy Build. (43) 3548–3557, http://dx.doi.org/10.1016/j.enbuild.2011.09.018.

[44] Peck, S.W., Callaghan, C., Kuhn, M.E., and Bass, B. (1999). Greenbacks from green roofs: Forging a new industry in Canada. Canada Mortgage and Housing Corporation. Ottawa, Canada.

[45] Kula, R. (2005). Green roofs and the LEED green building rating system, p. 141–153. In Proc. of 3rd North American Green Roof Conference: Greening rooftops for sustainable communities, Washington, DC. 4–6 May 2005. The Cardinal Group, Toronto.

Habitat Restoration and Biodiversity Conservation

Biodiversity is used to measure how healthy an ecosystem is. This is because a healthy ecosystem can support a wide range of organisms, and through the interaction of these organisms and the exchange of services, a balanced ecosystem is built.[46] Because of urbanization, a lot of native vegetation has been completely removed and with it the habitat and life force for many organisms. This is detrimental to the sustainability of the city because without the interconnected biological systems, our natural resources (food, water, air, soil, ect..) have an expiration date. Green roofs are a simple and cost effective way to integrate biodiversity into the current fabric of our urban ecosystem. Since extensive green roofs are practically inaccessible to the public, they have the potential to be undisturbed homes to microorganisms, insects, and birds that otherwise would not be able to thrive in a predominantly concrete geography.[47][48] In a study done in Switzerland, a huge biodiversity of spider and beetle species were found on 17 green roofs that were measured. It had only taken three years for the green roofs to collect an impressive number of species. Moreover, 18% of the spiders and 11% of the beetles were listed as endangered or rare.[49] Birds have been recorded using green roofs in England, Switzerland, and Germany.[50][51] One study in Michigan found that a 1 year old relatively large green roof (42,900 square meter) consisting of sedum and shallow soil was already habitat to 29 species of insects, 7 spider

[46] Sandifer, P. A., Sutton-Grier, A., & Ward, B. P. (2015). Exploring connections among nature, biodiversity, ecosystem services, and human health and well-being: Opportunities to enhance health and biodiversity conservation. *Ecosystem Services, 12*, 1-15. doi:10.1016/j.ecoser.2014.12.007
[47] MacIvor, J. S., & Lundholm, J. (2011). *Performance evaluation of native plants suited to extensive green roof conditions in a maritime climate*doi:https://doi.org/10.1016/j.ecoleng.2010.10.004

[48] Getter, K. L., and Rowe, D. (2006). The Role of Extensive Green Roofs in Sustainable Development, *HortScience HortSci, 41*(5), 1276-1285. Retrieved March 20, 2020, from: https://journals.ashs.org/hortsci/view/journals/hortsci/41/5/article-p1276.xml

[49] Brenneisen, S. (2003). The benefits of biodiversity from green roofs: Key design consequences, p. 323–329. In Proc. of 1st North American Green Roof Conference: Greening rooftops for sustainable communities, Chicago. 29–30 May 2003. The Cardinal Group, Toronto.
[50] Brenneisen, S. (2003). The benefits of biodiversity from green roofs: Key design consequences, p. 323–329. In Proc. of 1st North American Green Roof Conference: Greening rooftops for sus- tainable communities, Chicago. 29–30 May 2003. The Cardinal Group, Toronto.
[51] Gedge, D. (2003). From rubble to redstarts, p. 233– 241. In Proc. of 1st North American Green Roof Conference: Greening rooftops for sustainable communities, Chicago. 29–30 May 2003. The Cardinal Group, Toronto.

species, and 2 bird species.[52] These examples demonstrate how feasible it is to integrate biodiversity into urban environments and further strengthen our ecosystems. Basically, "if you build it, they will come".

Case Study for Future Potential of Green Roofs: New York City

I am choosing to analyze the potential of green roofs in NYC because it is one of the most metropolitan cities in the world as well as being a coastal city with a dense urban population and high rates of poverty. 60% of the city has a combined sewer system where " there is a single pipe that carries both storm water runoff and sewage from buildings. This mix of storm water and sewage is usually sent to a wastewater treatment plant.".[53] However, when there is a storm surge or a heavy precipitation event, the system overflows and instead of the mixture going to the wastewater treatment plant, it gets dumped in so called "CSO events" into the surrounding waterways.[54] This is a concern because of the effect on the water quality and recreational use of local water bodies.

In addition to this poor infrastructure, the climate of New York City (NYC) is experiencing changes: annual temperatures are increasing, storm surges are more frequent and intense, and the sea level is rising.[55] These patterns will continue to worsen due to the increasing concentration of greenhouse gases (GHG) in the atmosphere, and this is turn will continue to negatively impact the health and wellbeing of the population that call the city home. For these reasons, improving the ability to implement green roofs in a city like New York can go a long way, and if it can be done here it can be done anywhere.

Current Distribution of Green Roofs in the City of New York- 1 pages

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[52] Coffman, R.R., and Davis, G. (2005). Insect and avian fauna presence on the Ford assembly plant ecoroof, p. 457–468. In Proc. of 3rd North American Green Roof Conference: Greening rooftops for sustainable communities, Washington, DC. 4–6 May 2005. The Cardinal Group, Toronto.

[53] Combined Sewer Overflows. (n.d.). Retrieved fromhttps://www1.nyc.gov/site/dep/water/combined-sewer-overflows.page

[54] ibid

[55] IPCC, 2014: *Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Core Writing Team, R.K. Pachauri and L.A. Meyer

A mapping project conducted by The Nature Conservancy found that a little over 700 buildings in the city have green roofs, defined as " a roof that is partially or completely covered with vegetation, a growing medium such as soil, waterproofing, and a drainage system. "[56] Nearly 90% of these green roofs are located on private properties, most of which are residential. It seems that a lot of private property owners are interested in install green roofs, whether for aesthetic, ecological, or economic benefits. However, the two biggest green roof projects come from private institutional facilities- the Jacob Javits Convention Center in midtown Manhattan and the Barclay's Center in downtown Brooklyn. Most green roofs in total numbers, are small though. This is interesting because it demonstrates that even without a vast rooftop area, owners are still interested in installing green roofs in small spaces. This is definitely something to continue to encourage and help facilitate because in aggregate, these small green roofs can generate a lot of benefits.

This breakdown of green roofs in NYC looks promising. But let us contextualize the current distribution. In NYC, it is estimated that 42% of land use is building footprint, calculated from Open Data NYC building footprint.[57] Buildings take up the most area than any other impervious surface in the city. In turns out, the 700 buildings that include a green roof constitute 0.1% of NYC's buildings. This value clearly demonstrates that rooftops in NYC are an underutilized resource. There is room to grow. Additionally, a study done by Rositsa Ilieva from the Tishman Environment and Design Center at The New School, along with the mapping work from The Nature Conservancy, both demonstrate that the distribution of green roofs in the city is "unequal" or "inequitable".[58] The Nature Conservancy study found that most green roofs are "concentrated in midtown and downtown Manhattan. Of the 51 City Council districts, 30 have five or fewer green roofs, and eight districts (in the Bronx, Queens, Brooklyn, and Staten Island) have no green roofs at all."[59] Additionally, very few are located in the more vulnerable areas like those identified as heat vulnerable or important for storm-water capture. Ilieva found that little to no green roofs are in low income areas, heat vulnerable areas, areas with little to no parks and other on the ground green space, areas with great CSO volumes, and energy burdened areas.

[56] The Nature Conservancy. (2017). Look up to make room for a greener NYC.
[57] Open Data NYC. Building Footprints. Retrived from https://data.cityofnewyork.us/Housing-Development/Building-Footprints/nqwf-w8eh
[58] Rositsa T. Ilieva, Timon McPhearson. (2019). Social Equity and Green Roofs in New York City.
[59] ibid

These studies identify two pressing concerns for the implementation of green roofs in NYC. The first is that green roofs are not as widespread as they should be, especially in a city as dense and with a large rooftop footprint as New York. They are mostly implemented by private owners who do their own research and investment. There is no city-wide requirement to implement green roofs. The second issue is that the current distribution is not equitable.

In order for a tool to help promote implementation in the right places, it must help make the research and data on green roofs accessible while improving green roof outreach. The quantitative data on benefits as well as the spatial analysis on green roof distribution need to be translated in an effective way that a policy-maker, or private building owner can understand and use. Next, I will go into detail on the quantitative and spatial data I use, and on the thought process behind my design and development.

4. Methodology: Data, Design, and Development

Data

Building Suitability Analysis: Future Potential Dataset

The first study done by The Nature Conservancy had shown an emergence of an underutilized resource. The second study conducted was a mapping project to identify the suitable buildings for green roofs.[60] In this project, the aim was to identify green roofs with a large enough, flat enough surface area that can support the weight of a green roof. The latter criteria has been previously documented in other studies, where only buildings built before 1970 are the only ones to consider because during that time codes required greater roof live load requirements, built to withstand up to 50 pounds per square foot of rooftop live load.[61] The criteria of large enough and flat enough comes from industry experiences and talking with several installers of green roofs. Using building footprint, and an open source library for remote sensing imagery processing,

[60] The Nature Conservancy and Azavea (2019). Data on estimated potential for green roofs were provided as early work developed by The Nature Conservancy and Azavea, subject to refinement.
[61] Ackerma, K & Plunz, Richard & Conard, M & Katz, R & Dahlgren, Eric & Culligan, Patricia. (2011). The Potential for Urban Agriculture in New York City: growing capacity, food security & green infrastructure. New York, Urban Design Lab, Columbia University. 10.13140/2.1.4748.7683.

buildings pre 1970 with rooftop areas greater than 100 sq and a slope less than 9.5 degrees were considered.

This dataset is large and had been computationally expensive to work with, so I chose to only include the green roofs with a minimum of 1000 square footage of rooftop space; as compared to the original 100 square footage. I calculated the area of the polygons using QGIS, then using building query, I exported the dataset with the new cutoff.

The 1000 square footage was a cut off I made taking into account that the project largely depends on conveying the benefits of green roofs, and larger surface area rooftops would contribute more benefits. Preparing the dataset also included overlaying the polygons with NYC satellite imagery to remove any miscounted areas-flat areas that were not rooftops, such as wind turbines, and rooftops that already had green roofs or solar panels.

NYC Planning: PLUTO Tax Lot

In order to give the rooftops context, I used the NYC Planning Pluto dataset for land use categories, building classifications, boroughs, and building addresses.[62] I imported the dataset into QGIS and then I performed a tabular join using the "bbl" field.

Open NYC: Building Footprint

For building height data and year of construction, properties I wished to include in my tool, I used the Open NYC Building Footprint dataset.[63] I performed a tabular join with the field "Bin" here. Additionally, I used this data set on its own to represent all the rooftops in an area, not just the potential ones, for calculating the percentage of potential over total.

The Nature Conservancy: Current Green Roof Distribution

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[62] (2020). PLUTO and MapPLUTO. NYC Planning. www1.nyc.gov/site/planning/data-maps/open-data/dwn-pluto-mappluto.page.

[63] (2020). Open Data NYC. Building Footprint. https://data.cityofnewyork.us/Housing-Development/Building-Footprints/nqwf-w8eh

The current green roof distribution dataset comes from The Nature Conservancy.[64] I included it as a separate layer on the map because it is not involved in the future potential calculations or the future benefits of green roofs calculations.

Mapbox: 3D Building Data

Mapbox 3D building tileset was used to give the map a 3D effect. This tileset is built into Mapbox Studio.

Benefits Calculations Data: Heat, Habitat and Stormwater Management

For the benefit of heat, surface heat temperature was considered. Although green roofs can cool ambient temperature, and ambient temperature is the one that is more directly related to human health, it is harder to quantify and predict. For this reason, surface temperature was considered. Using Landsat 8 satellite imagery, a raster image was taken of New York during a particularly clear day, July 8, 2019. Then in QGIS, using Sonal Stats, I attached the surface temperature of the raster file to the potential green roof distribution. I then used an estimate for temperature reduction due to green roofs by comparing a patch of grass to concrete in the surrounding areas. This procedure included a lot of assumptions, therefore for now, I have left out the temperature benefit, until I can consult with a professional about the assumptions made.

Habitat benefit was straightforward. The area of the rooftop that is covered in vegetation is the habitat area, a 1:1 ratio here. This is because there is no reason to assume that any organism using the rooftop for habitat would be restricted from moving around the entire space.

Stormwater management benefit calculation was modeled from a study done by F. Viola on green roof runoff retention capacity in worldwide climates.[65] Taking into account current climate conditions, soil moisture dynamics, and soil depth a retention coefficient was determined and used to calculate retention capacity with different green roof sizes. The average rainwater per

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[64] (2016). The Nature Conservancy. Green Roofs Footprints for New York City, Assembled from Available Data and Remote Sensing. https://zenodo.org/record/1469674#.Xr72xy85TRY

[65] Viola, F., Hellies, M., & Deidda, R. (2017). *Retention performance of green roofs in representative climates worldwide* doi:10.1016/j.jhydrol.2017.08.033

square footage for NYC was determined from weather.gov and averaged for the last 5 years.[66] The soil depth was assumed 3-5 inches, because I am basing my calculations to the bare minimum of benefits that could be brought from an extensive low maintenance green roof.

With the data ready and cleaned, it is time to think about design and implementation.

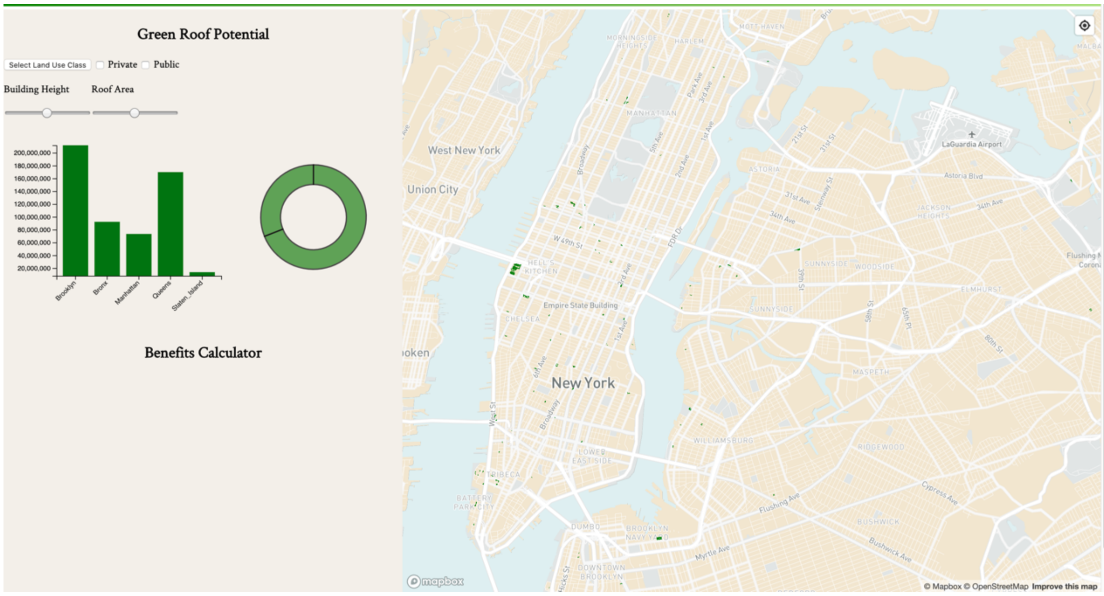
Design

The project design was challenging. I knew that the functionality needs to be strong, because I wanted it to be an application, with dynamic inputs and outputs based on user preferences. My audience is wide, so their preferences would be wide as well. I wanted to design something robust that knowledgeable policy makers would use to make informed decisions on where to invest in green roofs. The backend framework and scientific calculations needed to be strong. The project could not have a scroll-telling introduction either, I decided, because you would need to go through every-time you want to use the tool, and I thought that could be tiring. Additionally, I wanted the barrier of entry to use it to be extremely low that anyone interested in green roofs, no matter how knowledgeable about them they are, could use it as well. So it needs to have a friendly and basic interface, with well explained terms and sections. I was inspired by the Opportunity Atlas[67] dashboard because it was user friendly, but packed with information and statistics in a clear way. I thought about the concept of a dashboard, displaying statistics with a map incorporated for additional information.

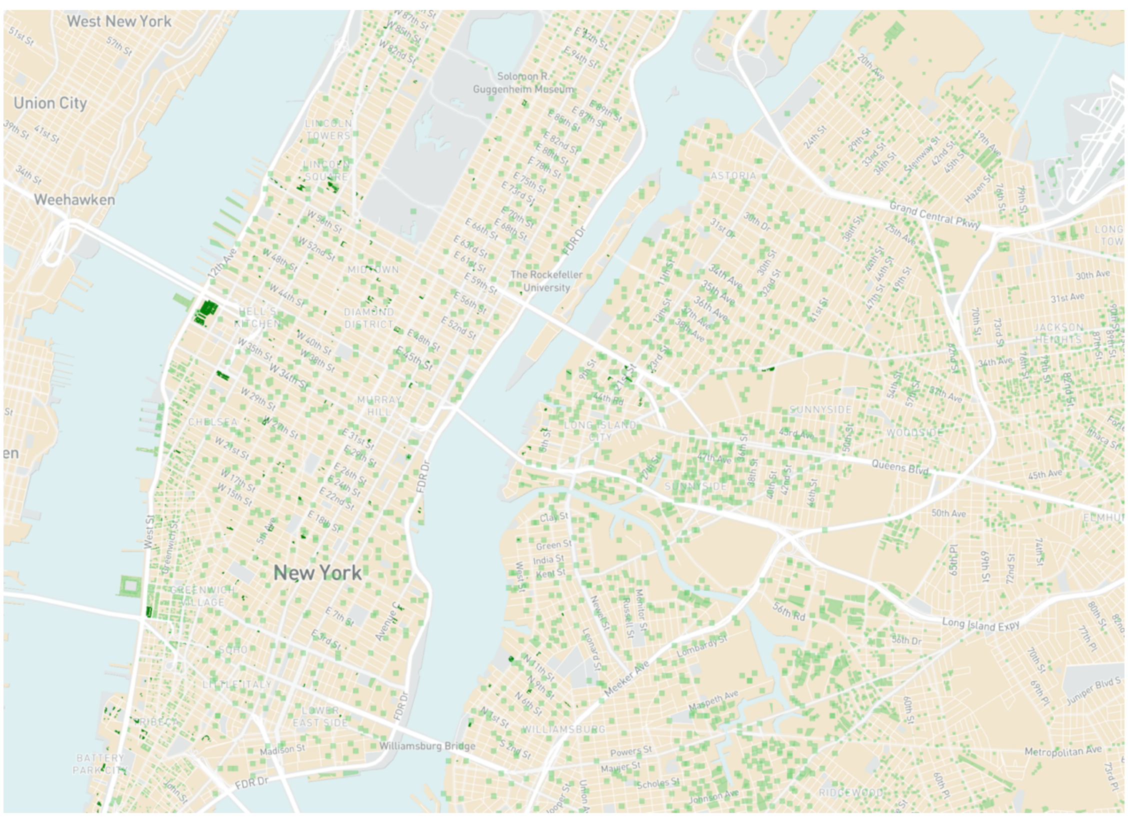
[66] Monthly and Annual Precipitation at Central Park. https://www.weather.gov/media/okx/Climate/CentralPark/monthlyannualprecip.pdf
[67] The Opportunity Atlas. (n.d.). Retrieved from https://www.opportunityatlas.org/

This is my first design iteration:

Figuring out my project will look and function like a dashboard, I needed to figure out its purpose. Reading a lot of articles on the legality of installing green roofs and community forums with questions people interested in green roofs posed, notably reddit's Green Roof community, I was able to assess that land use categories and building ownership determine whether a green roof could be installed, from a building suitability standpoint. So I decided that in order to make the tool useful for policy makers as well as the average person, including filters that allow for visualizing the distribution of green roofs and their benefits through building legality was a way to go. I also included rooftop area and building height because both properties determine the kind of benefits that could be brought. Building height, however, was later removed because the majority of building did not have a value. This is my second design iteration:



The map on its own:

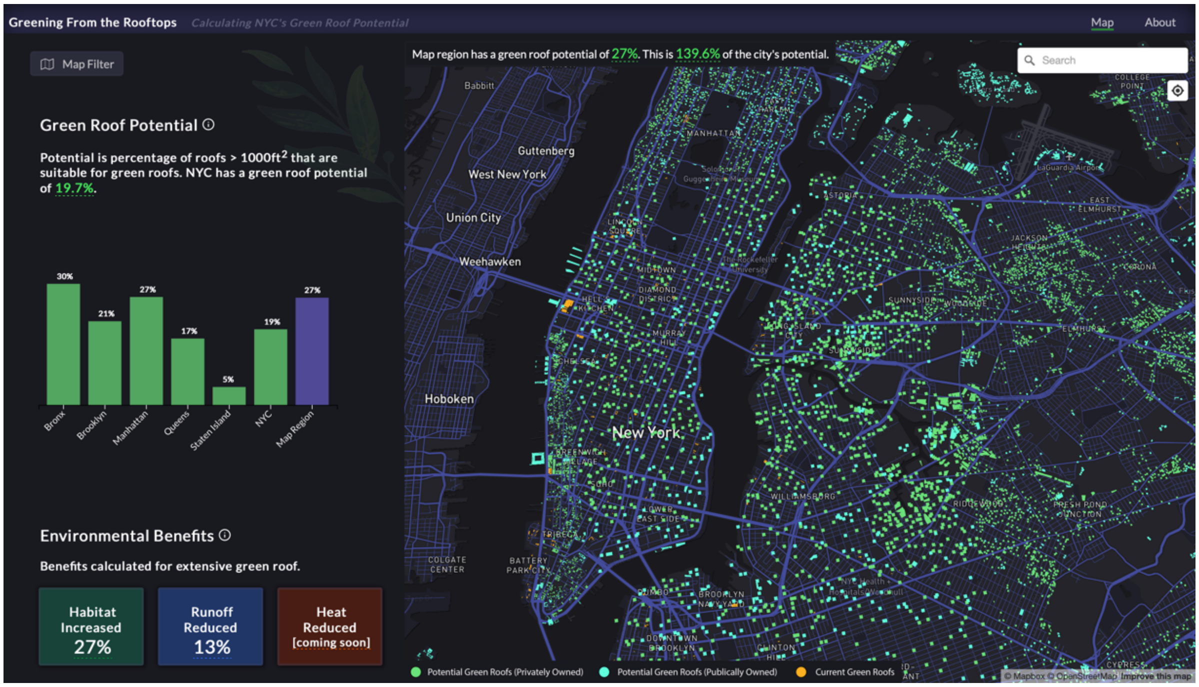


The colors however, had made it hard to visualize the future potential distribution in a meaningful way. I also did not like the bland look. I was talking about an exciting future where cities are living and breathing ecosystems, and the design seemed too boring to convey this excitement. Focusing on the idea of the future utopian city, and naturally having an affinity for the dramatic, I landed on this design:

My final iteration looks very similar to this one, expect that it allocates more space to the benefits calculations, which are an integral part of the project and not reflected in the first design exercises. I also noticed quickly that the map used a lot of space, while providing little additional information- I already have a bar chart with the potential distribution breakdown, why do I need the map to be a constant element taking up half the page? I realized that if I wanted to do a mapping visualization, which I did, I needed the map to do more than just show the distributions across boroughs. I needed it to provide a service. I also realized that the benefit calculations are very specific on area, some neighborhoods are hotter than others, some neighborhoods have a stormwater management issue, while other did not. So the benefits calculations needed to be based on an area more flexible than the potential distribution is. Being familiar with the green roof project from a couple of years ago, I was inspired by the benefits calculations the project did based on the map view box.[68] I was also becoming more and more comfortable with Mapbox GL's API, and was inspired by the extensive filtering features it offers an application.[69] The caveat was, that by itself, it does not seem like an intuitive way to use an application, at least not for policy makers and urban planners. However, when combined with a map filter, a tooltip on the map, an address geocoder, and a dynamic output I begin to bridge the gap between the traditional mapping functionality, and this new but powerful Mapbox GL feature. Finally, I removed the pie chart because it did not provide a substantial amount of information to justify the space it would take up.

The benefits output design was a challenge as well. The environmental benefits that are calculated were absolute numbers of habitat created and rainwater retained. To the scientifically informed user, they may make sense. But to the majority of people they were just large overwhelming numbers. Thinking about what the user would take out of the benefits calculations, I realized that I needed the values to be comparable. I needed percentages. That is why the main output from the calculations is the percentage increase in benefits if green roofs were installed. It made it easier to compare different areas based on benefits for example. That is why I included the sentence on top of the map that assessed the area's potential compared to the entire city. Now, the values are relevant to the user. If the city's potential is 20%, but your neighborhood is 50%, that means your neighborhood has a higher density of potential rooftops suitable for green roofs compared to the city. That also means you should go for it and invest! I did include the absolute numbers as well though, since I had them and they were information that could be beneficial to an informed user. But since, as I said, the values were very large and could be nonsensical to the average person, I included them in a flip-card style, so they only show when prompted. Final design:

[68] Serr, A. (2017). Retrieved from https://auchers.github.io/data-visualization-thesis/#/
[69] Mapbox. (n.d.). Filter features within map view. Retrieved from https://docs.mapbox.com/mapbox-gl-js/example/filter-features-within-map-view/

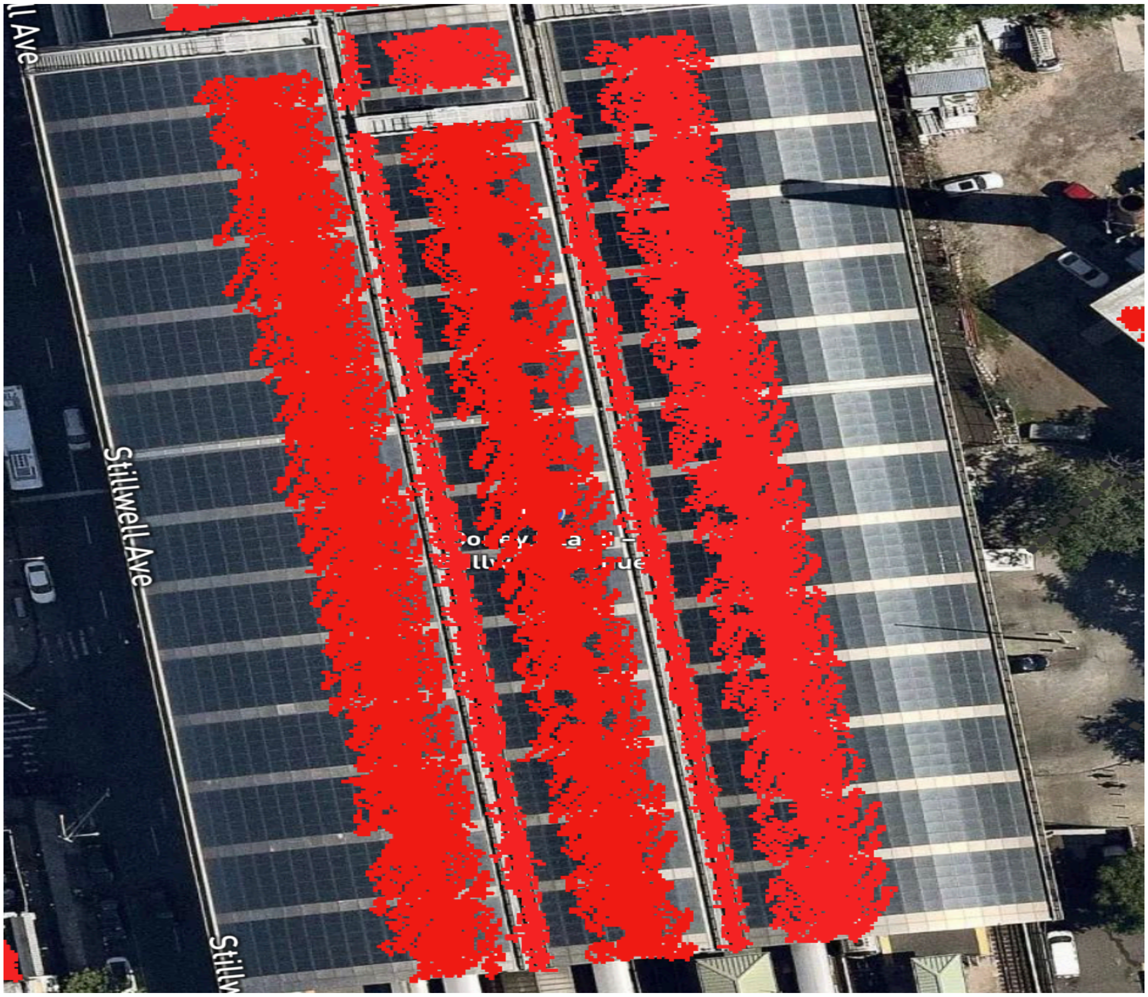


Now that there is a vision for the project, I will go into the development process with its trials and tribulations.

Development

Data Cleaning with QGIS

The first step in implementation is to get the data ready. As mentioned above, I used QGIS in order to clean and join the datasets. Specifically, the query builder and table joins, along with the geoprocessing toolbox. I also needed to remove any unavailable and miscounted areas, like this one that counted solar panels as potential green rooftops:



I then exported the datasets as GeoJSON from QGIS.

Mapping with Leaflet

In the first attempt to build this application, I used Leaflet to draw the map polygons onto a base layer I styled from Mapbox.

Here is a snapshot of it inside a wireframe I designed in AdobeXD:

The polygons did not look very good on the map (the snapshot does not demonstrate that because I zoomed in enough to an unpopular area for that reason). It was also extremely slow. I was distraught. I also imported my GeoJSON into MongoDB (in order to query based on the filters).

Database Set Up with MongoDB, Node, and Express

For this to work, I needed to set up a Node.js/Express/MongoDB application. I landed on this method because last semester we used Node.js/Express with AWS PostGres and it worked great. But I did not want to pay for PostGres after I graduated so I opted for MongoDB. I also did not need a relational database. I needed a nonrelational one. This is because I needed to query each "polygon" with all its characteristics. There was no added benefits to have multiple tables with all the characteristics broken down. If anything it might have slowed down my application.

Using a basic online tutorial[70], and days of trial and error I finally got my application set up with MongoDB compass.

After building my first query to get back all properties with a specific owner type, the application crashed because not enough memory on the VS Code disk!

```
.find(
    query,
      ($or: [
    { "properties.owner_type": "X" },
    { "properties.owner_type": { $ne: "C" } },
    { "properties.owner_type": { $ne: "M" } },
    { "properties.owner_type": "P" },
    { "properties.owner_type": null }
  ])
   )
   .toArray();
```

So I now have a broken express/node/mongodb application with data that is too big to function, and an extremely slow map. This was not working.

I decided to trim my dataset and only export the smallest borough. The same issue had arisen. This setup was not going to work.

Mapping with Mapbox

After a lot of research, and advice from my supervisor, I looked into Mapbox. It turns out they have a tileset data type that is made just for rendering really large datasets. So instead of using leaflet, I transformed my GeoJSON into a tileset using the command line and tippecanoe:

"tippecanoe -o reduced_dataffff.mbtiles -Z 10 -z 20 reduced_data22.geojson"

I was using a reduced dataset at this point as well, of only the rooftops over 1000 square footage because I was getting close to the deadline and began worrying that I had spent most of mid-March and early April, just simply scaling this project. Importing the Mapbox new map layer

[70] Bland, J. (2017). Using Node.js & Express.js to save data to MongoDB Database. Retrieved from https://codeburst.io/hitchhikers-guide-to-back-end-development-with-examples-3f97c70e0073

into my application worked beautifully. It was fast and elegant (because not all features rendered from a low zoom level). Now I needed to fix the MongoDB problem.

Since I was using Mapbox to render my map, and sense Mapbox tilesets have the building properties “in” them. I really only needed to connect the filtered building properties from MongoDB to the geometries in Mapbox based on a unique identification. Taking out the geometry from the MongoDB database made a huge difference in the size and speed of the query. I did this using JQ and the command line:

“jq ".features[].properties” -output reduced_data22.geojson > reduced_data22.json”

Having figured out how to connect the query for my map filters with Mapbox dataset, in order to have a functioning map that changes based on what attributes I ask my express app to bring back from MongoDB I need it to ask it to filter the current view. I did this using:

“map.setFilter("reduced-data22", roofFilter)”

Discovering the filter function, I do wonder if MongoDB was at all necessary. I am glad I learned how to develop an application, but for anyone reading this to implement something similar, I would first check if Mapbox GL’s filter function can be used dynamically (I now use it only to filter for the unique ids that MongoDB brings back from the subset I asked it to using the query).

Data Visualization with D3

Now that I have the map filtering right, and a query that brings back data on building properties, I needed to build my dashboard. It was natural for me to think of d3 for the bar chart (and pie chart at the time) I wanted to build. However, I think the Chart.js library would have been as effective and easier to use (I later discovered). So using the d3 library, I connected a query asking for area of future potential based on the filters selected divided by borough. I then standardized them using the total area in each borough regardless of filter.

Now I have two queries, one bringing back the filtered subset with unique identificationss that Mapbox will use to filter, another to bring back area by borough. To combine both filters into a promise (since express does not send two things, one one) I put them both into a single object:

"res.json({ filteredIds: FILTEREDIDS, areaByBorough })"

This concludes the potential breakdown section of the dashboard.

Benefits Calculation with Plain CSS and Mapbox GL

For the benefits section, using the "map.queryRenderedFeatures()" function in Mapbox GL, I was able to extract the area of the polygons within the view box. The areas were then inserted into the benefits equations I mentioned early in the data section. I then standardized the benefits by using the areas that have potential versus the total area in the view box.

5. Discussion and Conclusion

Findings

New York City has a green roof potential of 33%, including all rooftops. Only looking at rooftops larger than a thousand square footage, it has almost 20%. Bronx and Manhattan have the highest potential among the boroughs, 30% and 27% respectively. That is around 95.6 thousand potential rooftops. Another key finding is that private buildings were responsible for the greatest number of rooftops, but public buildings, predominantly schools and public housing units, were responsible for the largest rooftop space. When looking at the benefits these would bring, it would be a total habitat of 329.2 thousand square footage created, which would amount to 19.7% increase in the city, and a runoff reduction of 10%, which amounts to 42.1 billion gallons of water retained a year. We can see that a little goes a long way.

Assumptions and Limitations

1. Extensive rooftops of sedum 3-5 inches were only considered for the benefits calculations.

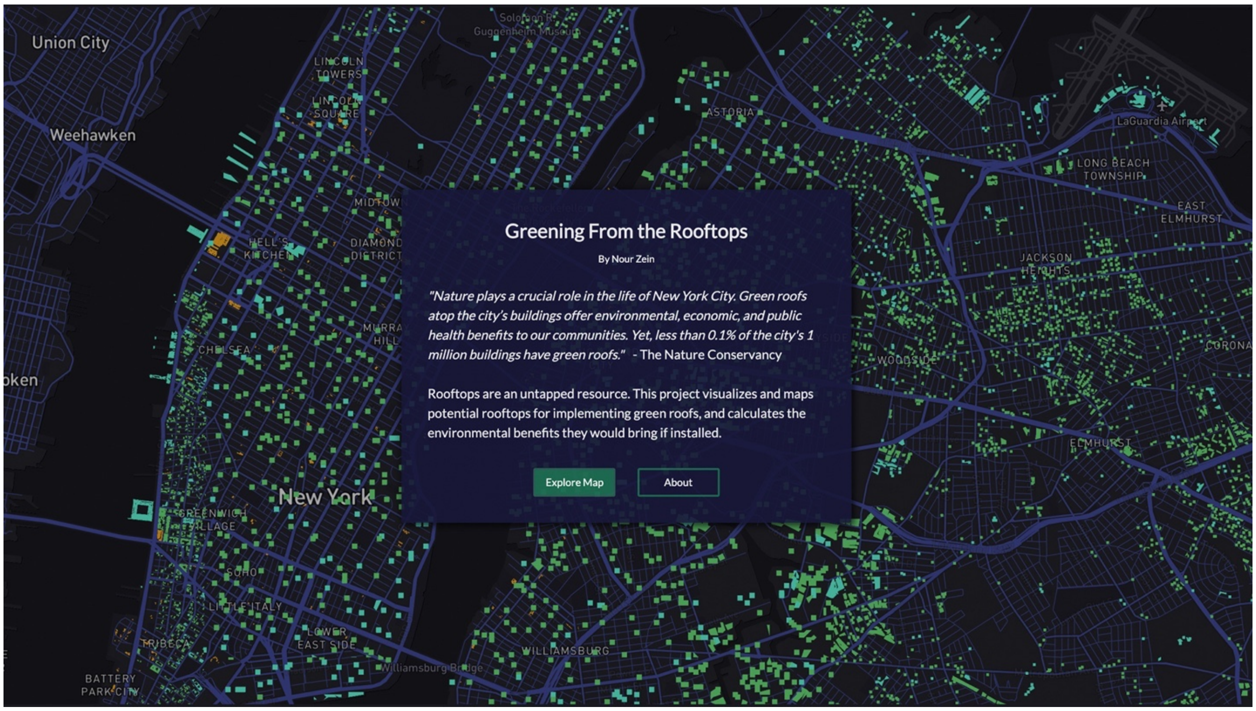
2. Surface temperature reduction benefits are only felt on the green roof and the immediate area around it.
3. Mixed property ownership and tax-exempt property ownership were grouped with public ownership for practical reasons.
4. Rooftops of only >1000 square footage were considered. The assumption is that rooftops smaller than this would not produce enough benefit to offset the economic cost of installation. There is also a limitation of project scope that did not allow for smaller rooftops to be analyzed as well.

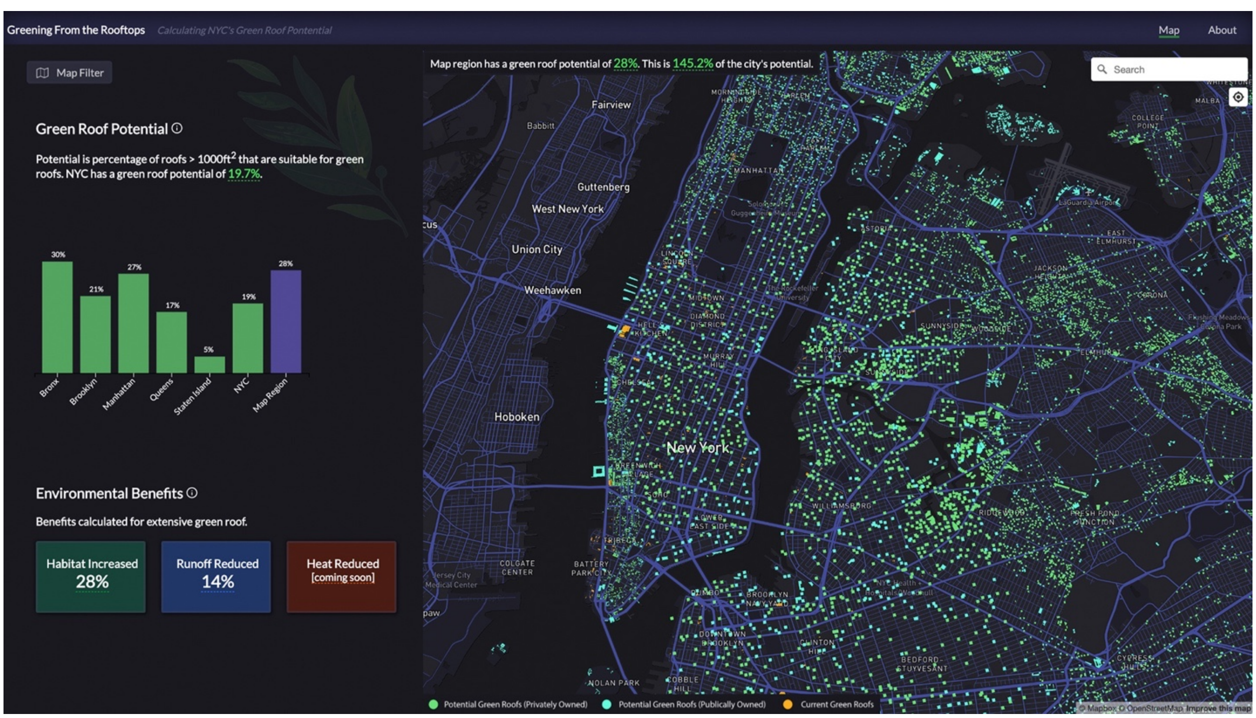
Future Directions

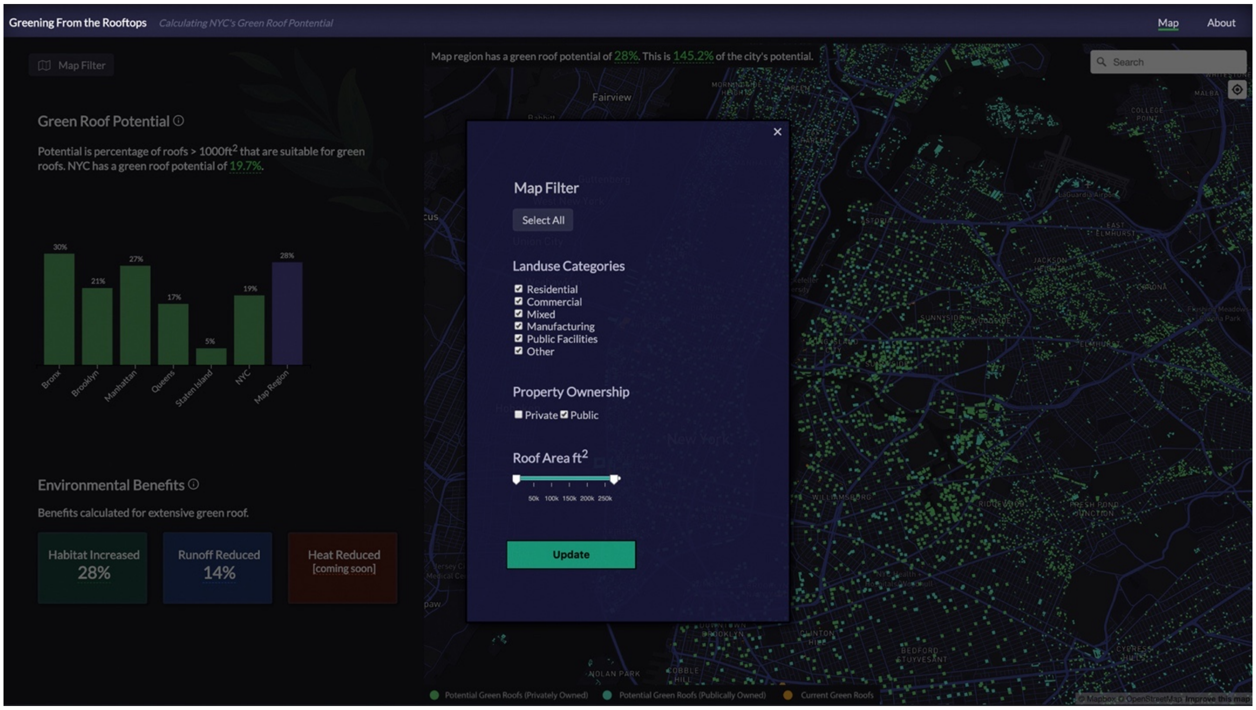
The objective of this project is to transform the research on green roof potential into an application that a wide range of users can benefit from. This is to promote and facilitate the use of green roofs in cities in order to improve their adaptive capacity and resiliency. However, in order to design a city that is truly sustainable, it must not only be ecologically sustainable but economically and socially as well. This project could benefit from incorporating quantitative economic benefits as well as qualitative social ones. It can also benefit from incorporating a distribution of social vulnerability, specifically low income communities suffering from heat related illness and water pollution, to target not only the areas with the most potential, but the areas with the highest vulnerabilities. Another avenue that I would have liked to explore if giving enough time is the publicly owned green roof potential, specifically school campuses and public housing units. The takeaway I have from this study is that we do not need to convince an entire population to adapt green roofs to make a difference. If the government simply took matters into their own hands and improved the infrastructures they are responsible for, I believe that that alone would make a tremendous impact.

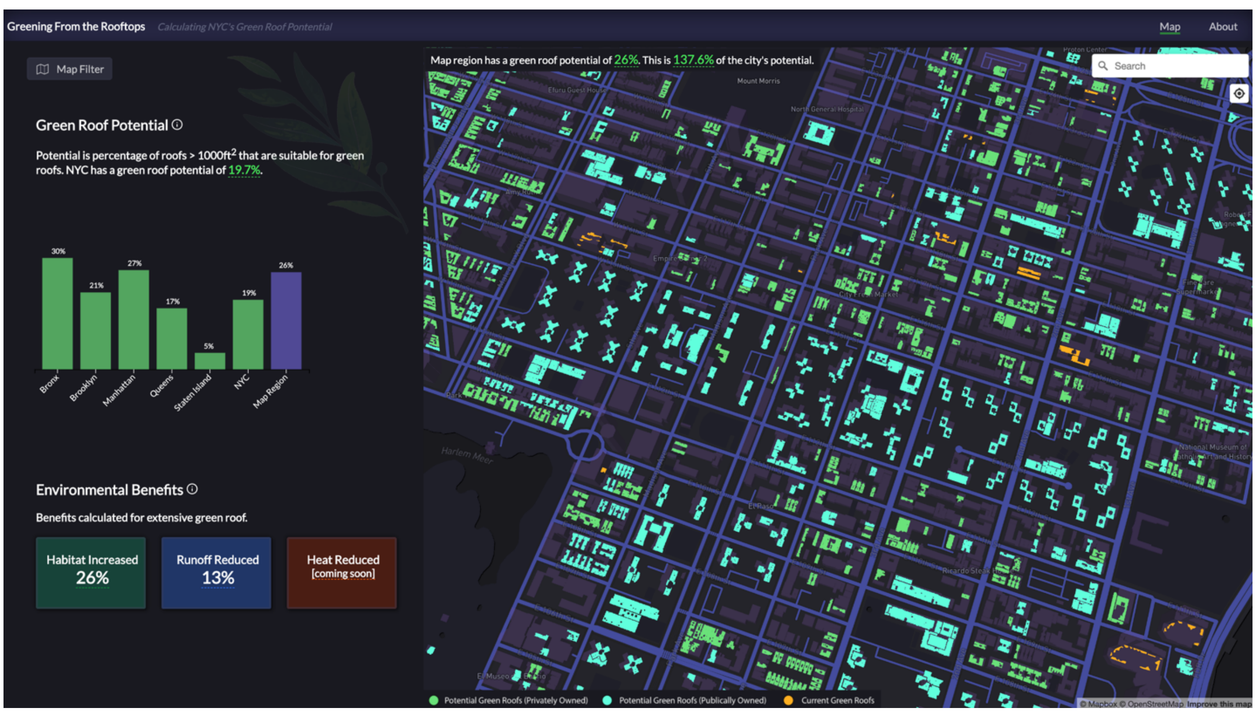
6. Appendix

Below are images of my data visualization, in the order in which they appear.






Greening From the Rooftops
Calculating NYC's Green Roof Pontential
Map
About
Map Filter
Green Roof Potential
Potential is percentage of roofs > 1000ft2 that are suitable for green roofs. NYC has a green roof potential of 19.7%.
Bronx
Brooklyn
Manhattan
Queens
Staten Island
NYC
Map Region
Environmental Benefits
Benefits calculated for extensive green roof.
Habitat Increased 28%
Runoff Reduced 14%
Heat Reduced [coming soon]
Map region has a green roof potential of 28%. This is 145.2% of the city's potential.
Map Filter
Select All
Landuse Categories
Residential
Commercial
Mixed
Manufacturing
Public Facilities
Other
Property Ownership
Private
Public
Roof Area ft2
Update
Potential Green Roofs (Privately Owned)
Potential Green Roofs (Publically Owned)
Current Green Roofs


Greening From the Rooftops
Calculating NYC's Green Roof Pontential
Map
About
Map Filter
Green Roof Potential
Potential is percentage of roofs > 1000ft2 that are suitable for green roofs. NYC has a green roof potential of 19.7%.
Bronx
Brooklyn
Manhattan
Queens
Staten Island
NYC
Map Region
Environmental Benefits
Benefits calculated for extensive green roof.
Habitat Increased 26%
Runoff Reduced 13%
Heat Reduced [coming soon]
Map region has a green roof potential of 26%. This is 137.6% of the city's potential.
Search
Potential Green Roofs (Privately Owned)
Potential Green Roofs (Publically Owned)
Current Green Roofs

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