GREEN ROOFS IN THE TROPICS; DESIGN CONSIDERATIONS AND VEGETATION DYNAMICS

By

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a thesis submitted to the

DEPARTMENT OF ENVIRONMENTAL SCIENCES

FACULTY OF NATURAL SCIENCES

UNIVERSITY OF PUERTO RICO

RIO PIEDRAS CAMPUS

In partial fulfillment of the requirements for the degree of

MASTER IN SCIENCE

July 2017

Rio Piedras, Puerto Rico

This thesis has been accepted by the faculty of the

DEPARTMENT OF ENVIRONMENTAL SCIENCES

FACULTY OF NATURAL SCIENCES

UNIVERSITY OF PUERTO RICO

RIO PEDRAS CAMPUS

In partial fulfillment of the requirements for the degree of

MASTER IN SCIENCE

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DEDICATION

To my family.

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ACKNOWLEDGEMENTS

During this process there are many people who deserve to be acknowledged for their constant support and help. I would like to start by thanking my advisor Jess Zimmerman for his guidance and assistance, and my committee members Grizelle González and Gary Gervais as well. Particularly I would like to recognize Rosa Saez, who helped me through the data collection process and Andrew McFadden, who was constantly available and helpful. In general, thanks to many other colleagues and professors who gave me ideas and solutions in moments that it was needed the most, thanks to the US Forest Service International Institute of Tropical Forestry (IITF), and the Department of Environmental Sciences. Thanks to the Faculty of Natural Sciences in the University of Puerto Rico, the Dean of Graduate Studies (DEGI), and the Luquillo Long-Term Ecological Research Program for their financial assistance. And lastly, many thanks to my family for their continuing support.

INTRODUCTION

Environmental conditions around the globe are constantly changing and facing new challenges. The triggers of those changes are linked to the dynamic economic factors, social aspects and human population growth, among many other stressors. As stated in the Brundtland Report for the United Nations (Harlem Brundtland 1987), global population is not only expected to continue rising but is also presumed to be concentrated in urban areas and high density zones. This poses major environmental issues that need to be addressed from a holistic perspective in order to meet the desired sustainability goals in all aspects of our society (Berardi, GhaffarianHoseini, and GhaffarianHoseini 2014). Sustainability has been discussed in numerous forums that intend to converge in a worldwide policy towards a list of problems and solutions that guide society's actions and future.

To achieve sustainability using the resources already available and taking advantage of the current urban situation, described as a dense and crowded zone, many have thought of green roofs (GR) as a plausible solution that, integrated with other remediation and mitigation actions, can lead the way to a more sustainable society (Berardi, GhaffarianHoseini, and GhaffarianHoseini 2014; Beyhan and Erbaş 2013; Vijayaraghavan 2016; Olsen 2015). European countries were the precursors of such strategy and have established the basis of knowledge in the GR area; some countries have already implemented public policies to incorporate this trend as one of the multiple actions to be taken in the journey to sustainability (B. Dvorak and Volder 2010; Oberndorfer et al. 2007; Peng Lihua 2012). In order to achieve better outcomes from GR ecosystems and to design those to obtain the desired benefits, multiple studies were conducted throughout the years to generate a knowledge foundation that would be updated throughout research results.

The tropics is an area that possesses a great pool of the globe's biodiversity, and a unique climate to be understood on many topics. Green roof implementation in the tropics has been scarce and more information is needed in order to adapt this novel ecosystems to the conditions that these zones have and that are greatly different from temperate areas (Speak 2013; Lugo and Rullán 2015). A gap of information is then recognized in this area of the environmental sciences, and needs to be filled with research that covers all areas from adaptability of green roofs, to implementation, design, outcomes and policies. The work done in this thesis aims to compile a literature review under the scope of a tropical setting and to cover basic ground on the vegetation dynamics of green roofs in the tropics.

Chapter I of this thesis collects general information of green roofs and evaluates the principles of this topic. It covers GR description, design, potential benefits, and climate change. The chapter also includes information about the green roofs in the tropical zones around the globe, and more specifically in Puerto Rico. In Chapter II a vegetation analysis of 4 GRs in San Juan, Puerto Rico was undertaken. The International Institute of Tropical Forestry (IITF) facilities were used as well as an older green roof located in the University of Puerto Rico. The IITF green roofs possessed the characteristic of being design specifically as a research platform with a variety of depths throughout the building which increased the number of distinct GR ecosystems in the project (Lugo and Rullán 2015). By the end of this study an initial approach to the topic would be available in terms of design considerations, a list of potential species for green roofs design, and an idea of information that is lacking could enlarge our knowledge of GR as novel ecosystems that serve as mitigation tools in our modern society.

References

Berardi, Umberto, AmirHosein GhaffarianHoseini, and Ali GhaffarianHoseini. 2014. "State-of-the-Art Analysis of the Environmental Benefits of Green Roofs." *Applied Energy* 115 (February): 411–28. doi:10.1016/j.apenergy.2013.10.047.

Beyhan, Figen, and Meltem Erbaş. 2013. "A Study on Green Roofs with the Examples from the World and Turkey." *Gazi University Journal of Science* 26 (2): 303–18.

Dvorak, Bruce, and Astrid Volder. 2010. "Green Roof Vegetation for North American Ecoregions: A Literature Review." *Landscape and Urban Planning* 96 (4): 197–213. http://www.sciencedirect.com/science/article/pii/S0169204610000782.

Harlem Brundtland, Gro. 1987. "Report of the World Commission on Environment and Development : Our Common Future."

Lugo, Ariel E, and Jeannette Rullán. 2015. "The Conservation Message of the Rehabilitated Facilities of the International Institute of Tropical Forestry," no. November.

Oberndorfer, Erica, Jeremy Lundholm, Brad Bass, Reid R. Coffman, Hitesh Doshi, Nigel Dunnett, Stuart Gaffin, Manfred Köhler, Karen K. Y. Liu, and Bradley Rowe. 2007. "Green Roofs as Urban Ecosystems: Ecological Structures, Functions, and Services." *BioScience* 57 (10): 823. doi:10.1641/B571005.

Olsen, Kerby. 2015. "EVALUATING URBAN DESIGN STRATEGIES FOR CLIMATE CHANGE by." California Polytechnic State University, San Luis Obispo.

http://digitalcommons.calpoly.edu/cgi/viewcontent.cgi?article=2490&context=theses.

Peng Lihua, Lilliana. 2012. “Green-Roof Thermal Effects in the Context of Climate Change and.” University of Hong Kong. http://hub.hku.hk/bitstream/10722/181517/1/FullText.pdf?accept=1.

Speak, Andrew Francis. 2013. “Quantification of the Environmental Impacts of Urban Green Roofs.” https://www.escholar.manchester.ac.uk/api/datastream?publicationPid=uk-ac-man-scw:203993&datastreamId=FULL-TEXT.PDF.

Vijayaraghavan, K. 2016. “Green Roofs: A Critical Review on the Role of Components, Benefits, Limitations and Trends.” *Renewable and Sustainable Energy Reviews* 57 (May): 740–52. doi:10.1016/j.rser.2015.12.119.

CHAPTER 1. Green Roofs: a Literature Review

Abstract

This review emphasizes the beneficial aspects of green roof implementation, identifies benefits and weaknesses, points out information gaps, and sheds light in general factors, and stresses out the importance of research of green roofs in the tropics for a suited implementation and the creation of new public policies. Green roofs are clearly a plausible solution to some of the current problems related to urban areas, pose as noninvasive mitigation tools for most places depending on resources availability and local conditions, and have a large list of interdisciplinary areas that need to be explored. Even when some aspects are mostly settled there is a need for farther development in many subthemes of the green roof topic. Allocation, applicability and durability are themes that still hold many questions, especially in the tropics and in Puerto Rico. Throughout the review we collected information required for the good design and suitable implementation of green roofs, some examples of design adaptation of green roofs in Singapore, and an article that models the implementation of this system in the coastal zone of San Juan, PR.

Key Words: Green roofs review – tropical green roofs– literature review.

Introduction

The rapid economic growth of countries and the accelerated urban increase, along with the multiple problems associated with these areas have created the necessity for the implementation of new solutions to the challenges of urban living (Berardi 2014). Rapid urban expansion at the expense of green areas translates into a decrease in canopy interception which causes the temperature to increase and air humidity to decrease (Vijayaraghavan 2016), among other issues. Green roofs are presented as one of the multiple mitigation tools that can be incorporated into a plan to offset climate change effects, urban expansion problems, and other possible concerns related to human intervened ecosystems. As green roofs have become more popular in the recent decades and their implementation has expanded beyond Europe, the urge to understand how this novel ecosystems function has arisen in many areas. Scientists from multiple disciplines have dedicated their efforts in the learning, improvement, and development of green roofs. Ecologists, on one hand, are interested in studying how these human designed ecosystems resemble natural ground level ones, in terms of composition, function, service provision, etc. Various studies have been conducted to assess the novelty and suitability of green roofs in non-tropical areas, but very few have evaluated performance of green roofs in tropical settings (Lugo and Rullán 2015). Therefore a need to study and understand these systems emerges for these zones around the globe. Studies that provide a wide scope of themes evaluating their functionality, viability and adaptability in tropical environments would become a vital tool in the mitigation and adaptation of countries in these areas under the effects of climate change and urban growth conditions.

Literature review

The potential benefits of green roofs, climate change adaptation, green roof design, and the implementation of green roofs in the Tropics, were the four main themes of this literature review. Among this a list of subthemes was developed for better understanding of the topic: direct and indirect effects to local climate favor by the implementation of green roofs, suitable species composition and soil depth in the ecosystem design, and applicability in the tropics.

Description of Green Roofs

Green roofs can be called by different names, and even though this seems like a shallow argument, the identification of it suggests something about the use and purpose of green roofs. “Eco roofs” often signify the ecological services provided by it, “living roofs” may refer to the wildlife habitat provision, and “garden roofs” can be interpreted as an aesthetical purpose or an agricultural one. But no matter the name, often the purpose of green roofs are linked to the enhancement of energy efficiency, the provision of green spaces in urban areas that are lacking them, and lastly a new trend of urban agriculture has taken place in these roofs (Berardi, GhaffarianHoseini, and GhaffarianHoseini 2014). As indicated in a state-of-the-art analysis (Berardi, GhaffarianHoseini, and GhaffarianHoseini 2014), the development of green roofs is an area that requires the contribution of multiple sectors and disciplines, just to name a few: architects and engineers, horticulturists and ecologists, contractors and urban planners.

Experts from interdisciplinary backgrounds continue to develop green roof design and structure, and the research focus are vastly diverse and can cover from green regeneration in urban areas, to energy-related performance of buildings and other structures, as well as the enhancement of ecological biodiversity, ecological habitats, air quality improvement, and also urban hydrology and storm water management (Berardi, GhaffarianHoseini, and GhaffarianHoseini 2014; Li and Babcock 2014; Bolaños-Silva and Moscoso-Hurtado 2011; Olsen 2015); Fig. 1). No matter the discipline, in all cases what is common to the research is the classification or description of the attributes of green roofs. There are two main categories in which green roofs can by classified, either intensive or extensive. An intensive green roof is often defined as a roof covered with vegetative material that consists of a deep substrate layer. On the opposite side extensive green roofs are shallower in depth. Intensive green roofs are more expensive than extensive ones, are mostly accessible areas with recreational purposes, have heavier weight and high plant diversity (Berardi, GhaffarianHoseini, and GhaffarianHoseini 2014; Table 1)

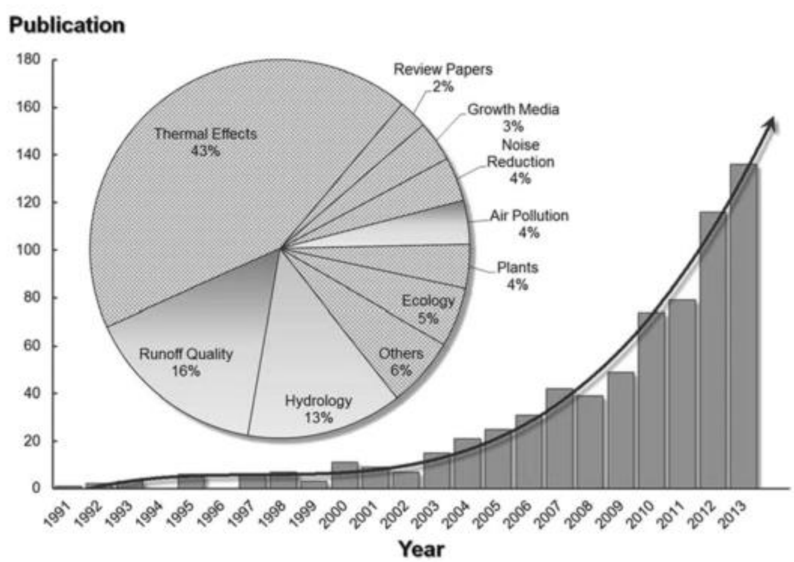

Figure 1. Published research papers on green roofs in the las two decades show a rapid growth trend. Source: (Li and Babcock 2014)

Table 1. Classification of green roofs and their main attributes with supporting literature. Source: (Berardi, GhaffarianHoseini, and GhaffarianHoseini 2014)

Table 1
Classification of green roofs and their main attributes with supporting literature.

Main attributes	Extensive	Intensive	Source
Thickness of growing media	Below 200 mm	Above 200 mm	[18,34]
Accessibility	Inaccessible (fragile roots)	Accessible (usable for recreation purpose)	[18,34,38,39]
Weight	60–150 kg/m^2	Above 300 kg/m^2 (may require a reinforced structure)	[18,34,38,39]
Diversity of plants	Low (moss, herb and grass)	High (lawn or perennials, shrub and tree)	[7,18,34,38,41]
Construction	Moderately easy	Technically complex	[39,41]
Irrigation	Often not necessary	Necessity of drainage and irrigation systems	[7,38,39,41,43–45]
Maintenance	Simple	Complicated	[5,28,53]
Cost	Low	High	[11,23,39,49]

Installation of green roofs has to consider several factors, for example the size of the roof, the structural strength of the building and the maintenance cost in the long run. Also the procedure of the installation can vary from a pre-cultivated, to a modular, or a layered type, depending on how simple or fast the process would be, the type of system and the cost of the building process (Table 2, Berardi et al. 2014). The way a green roof is structured or implemented can also be a way of classification. But regardless of the type of structure or green roof, there are certain amount of layers that need to be incorporated into a well-designed and complete system. The most common layers in the construction of green roofs, both intensive and extensive, from the bottom up are: the protection layer, the root barrier, the drainage layer, filter layer, water retention, the substrate, and the vegetation (Bozorg Chenani et al. 2014; Fig. 2). Studies suggest that more than any other factor, economics is what directs the composition and design of the green roofs. Bozorg et al. (2014) state that "the composition of the substrate can vary from one country or area to another due to the price, availability of raw materials, etc."

Table 2. Design construction classification of green roof systems. Source: (Berardi, GhaffarianHoseini, and GhaffarianHoseini 2014)

Table 2
Design construction classification of green roof systems [15,28,39].

Issue	Pre-cultivated system	Modular system	Complete system
System	Pre-planted	Pre-planted	Layered system
Weight	Low	Average	Generally high
Installation	Simple and fast	Simple and fast	Complex
Maintenance	Simple	Simple	Complex
Cost	Low	Average	High

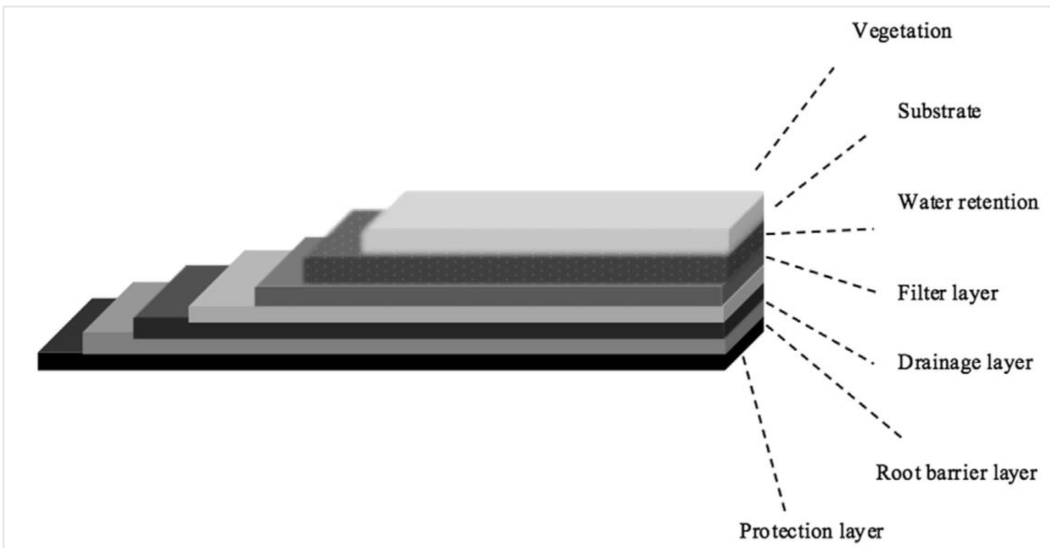

Figure 2. Layers often used in green roofs.
Source: (Bozorg Chenani, Lehvävirta, and Häkkinen 2014).

Green Roof Design

Green roofs are consider novel ecosystems in which the design takes in consideration several key aspects for a better performance or desire outcomes, for instance, species composition in relationship with the desired function or service to be provided by the green roofs. In that sense what some experts suggest is to build taking in consideration functional diversity (FD), in the belief that greater biodiversity would translate into ecosystem stability (Van Mechelen et al. 2015). Authors think that by carefully selecting the pool of species that would form part of the design the stability, outcomes, durability and resilience of the ecosystem increases (Berardi, GhaffarianHoseini, and GhaffarianHoseini 2014; Van Mechelen, Dutoit, and Hermy 2015; Van Mechelen et al. 2015). Also there has to be taken in consideration that the space to develop such ecosystems is limited, in that sense “the goal is to achieve optimal allocation of a limited amount of resources by maximizing the FD” (Van Mechelen et al. 2015).

Soil depth is another important aspect that needs to be carefully examined besides plant composition. In most of the cases this layer is made of a mixture of different proportions of compost with: crushed bricks, expanded clay, and/or clay-loam soil; in addition the mixture may contain animal manure and green wastes such as plant pruning and debris (Ondoño, Martínez-Sánchez, and Moreno 2015). The soil depth is relevant for multiple reasons: the type of plants it can support, the amount of insulation that it can provide to the building in terms of external heat, and some sound isolation provided by green roofs. This is also dependent on soil depth, water filtration and/or degradation, among many other aspects.

<u>Potential Benefits of Green Roofs</u>

Before deciding what type of green roof and which design is better suited for an area, a generalized perspective of the potential benefits is appropriate. Arguments can vary depending on the defending side’s position or background but coincide in establishing that green roofs present many economic and social benefits, in combination with several environmental advantages (Vijayaraghavan 2016, Karteris et al. 2016, Li and Babcock 2014). The potential environmental benefits are strongly correlated with the type of roof itself, because depending on the design there would be certain limitation. For instance Berardi et al. 2014 state that "the types of plants that can be utilized for extensive green roofs are limited, and both the energy performance and storm water management potentials are relatively low." Below there is a description of some of the most common benefits associated with green roofs along with some of the associated downsides of each service.

Storm Water Attenuation

The management of surface waters or runoff in urban areas has become a problem when large precipitation events occur, and in some places with large impervious areas, even with small amounts of precipitation (Romnée, Evrard, and Trachte 2015). Green roofs present a solution for attenuating the amount of water in runoff. Via collection on roof tops, water gets either, intercepted, retained or transpired by plants. It can also be stored in the porous substrates that are generally high in water holding capacity (WHC), a desired feature on extensive green roofs that can be obtained by a careful selection of the growing media mixture (Vijayaraghavan 2016). A study by Nagase and Dunnett (2012) examined different plant species in terms of their water retention capacity and found grasses were more efficient in reducing runoff, followed by forbs and sedum. This experiment was done in a greenhouse with a controlled environment. Similar tests need to be performed in tropical settings in order to obtain plant performance in storm water reduction. To offset these benefits a problem that has been pointed out by some studies e.g. (Teemusk and Mander 2007) is that, depending on maintenance and composition of layers water quality can be degraded due to accumulation of some nutrients or the use of pesticides.

Thermal Benefits

Green roofs are often studied from the energy-related performance perspective. In this sense must studies have identified living roofs as very good cooling features in many areas (Saadatian et al. 2013). Green roofs work by providing shade and insulation, and by elevating the thermal mass of the structure. By enhancing the isolation, less heat is stored at the surface of the building, making inner cooling systems more efficient and therefore reducing energy consumption. But this has to be evaluated carefully because the insulation is going to be strongly dependent on plant type and growing medium depth. Some also argue that it is important to consider building use, amount of area cover by the green roof, and seasonality (Vijayaraghavan 2016). Another important aspect to take in consideration is the potential of green roofs to mitigate the heat island effect, although this would require a large-scale application of green roofs in urban areas. A study conducted in southern Australia models the implementation of different percentages of green roof implementation and shows that as green roof coverage increases, the urban heat island (UHI) effect decreases (Razzaghmanesh, Beecham, and Salemi 2016; Fig. 3).

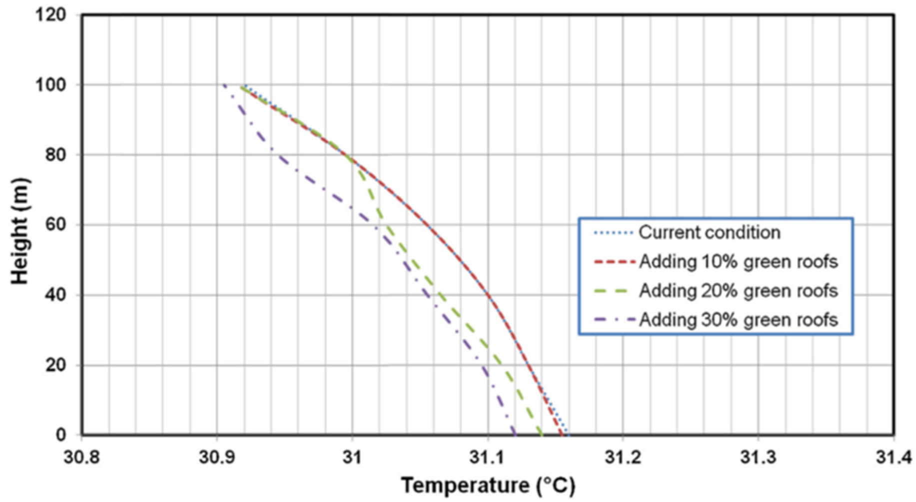

Figure 3. Comparison of scenarios for adding green roof cover on top of buildings. Source: (Razzaghmanesh, Beecham, and Salemi 2016).

Water Quality Enhancement

Green roofs serve as buffers for acid rain and mitigate peak flow events, but the water quality is still a critical issue. In most cases there have been good feedbacks by green roof implementation in water quality, but sometimes as pointed before, water quality can face degradation, especially in deeper substrates, due to accumulation of nutrients or the use of fertilizers (Malcolm et al. 2014). In general the evaluation of green roofs runoff show that the concentration of many contaminants and pollutants were lower than in conventional roofs (Vijayaraghavan 2016).

Noise Reduction

Noise reduction is a less explored benefit from green roofs, but is fairly easy to predict. Van Renterghem and Botteldooren (2011) state that this green structures can facilitate noise reduction either by isolating internal and external environments, or by refracting sound waves. The layers act as a barrier between the external and internal environments (Peng Lihua 2012) or can serve as wave absorbers or redirectors at the surface level (Speak 2013; Li and Babcock 2014; Cuerda et al. 2000).

Air Pollution Reduction

For the assessment of air pollution reduction there are direct and indirect effects that can be assessed. For instance, there is the direct effect of plants cleansing of the environment, which is a widespread suggested technique for urban areas (Vijayaraghavan and Joshi 2014; Vijayaraghavan 2016). The indirect effects are harder to detect but equally important. By reducing energy consumption in most buildings, at a larger scale this would translate into lower fossil fuel burning, which means better global climate (Vijayaraghavan 2016). The offset of this benefit is that larger plants provide a better outcome, therefore, intensive green roofs can help mitigate air pollution better than extensive ones.

Many other benefits are associated with green roofs. The enhancement of aesthetical appeal of buildings is one, not only provided in the individuality of the structure itself, but at a larger scale in the national economy as value of property increases. Green structures can also help restore biodiversity, shelter wildlife, and even protect the roof membrane from excessive UV light, wind, and heat (Vijayaraghavan 2016; Berardi, GhaffarianHoseini, and GhaffarianHoseini 2014; Ponni and Baskar 2015; Speak 2013; Sihau 2008; Van Mechelen et al. 2015; Srivastava 2011; Jim 2015; Gargari et al. 2016). But even when a few of the limitations of green roofs where already mentioned, it is important to point out that the most limiting factor, beside implementation and maintenance cost, is the identification of the purpose itself. Studies suggest that in most cases green roofs are not built for all of the good environmental outcomes listed above, but merely for aesthetical purposes. Vijayaraghavan (2016) compiled some of the most common constraints identified by people regarding green roof implementation (Fig. 4).

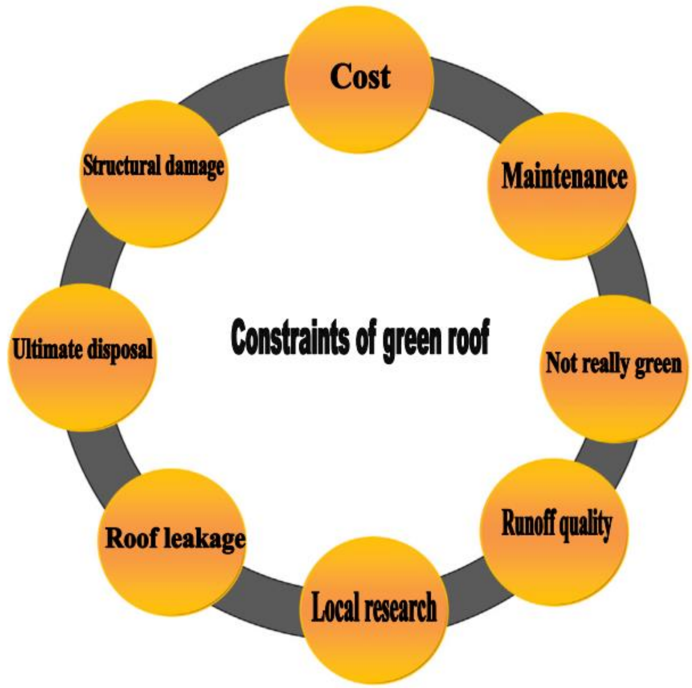

Figure 4. General constraints of green roof according to public perspective.
Source: (Vijayaraghavan 2016).

Green Roofs and Climate Change

As urban areas around the globe are currently increasing rapidly due to major economic changes in most countries (Parnell 2016, He et al. 2016), many of the effects associated with urbanization have reach an undesired stage. Green roofs pose a possible remediation and mitigation tool for some of the problems associated with urban areas. As pointed out by Razzaghmanesh et al. (2016) the urban heat island effect is one of the most common consequences of altered climate in cities, this being due to a combination of many factors such as low amount of green areas, high density of buildings, large impervious areas, and the burning of large amount of fossil fuels, among others. One of the most important factors associated with heat balance is the level of albedo, which is largely determined by the material and its physical properties, such as reflectance, heat capacity and heat absorbance.

Most structures in cities have low albedo, which means they retain most of the heat they receive instead of reflecting it. Different type of surfaces have very different levels of albedo (Peng Lihua 2012, Table. 3). Another proposed solution for the urban heat island (UHI) effect are cool roofs, which are roofs covered with a highly reflective membrane that minimizes heating and increases reflectivity (Olsen 2015). Even though green roofs have lower albedo that this cool ones, the associated benefits in relationship with thermal effects are much higher in green than in cool roofs (Vijayaraghavan 2016). The mechanisms with which green roofs operate are complex and have multiple stages. Peng Lihua (2012) summarized most of it in a schematic view (Fig. 5). Green roofs improve thermal balance by two main strategies (Peng Lihua 2012), either by shading or by cooling. Shading is translated into a decrease in surface temperature which has subsequent effects such as decreases in heat penetration, long wave radiation, and sensible heat flux. On the other hand cooling works by increasing latent heat flux which means decrease in air temperature and increase in air humidity, directly counteracting the urban heat island.

Table 3. Albedo of different land surface types. Source: (Peng Lihua 2012)

Surface type	Albedo
Green	0.15
Bare soil	0.17
Concrete	0.37
Highly reflective gray paint	0.36
Highly reflective white paint	0.74

But it is not only by regulating thermal conditions that green roofs act towards climate change, green roofs can be good sinks for many contaminants commonly found in greater concentrations in urban areas. For instance studies show that green roofs can trap contaminants in both, solid and gaseous stages (Li and Babcock 2014).

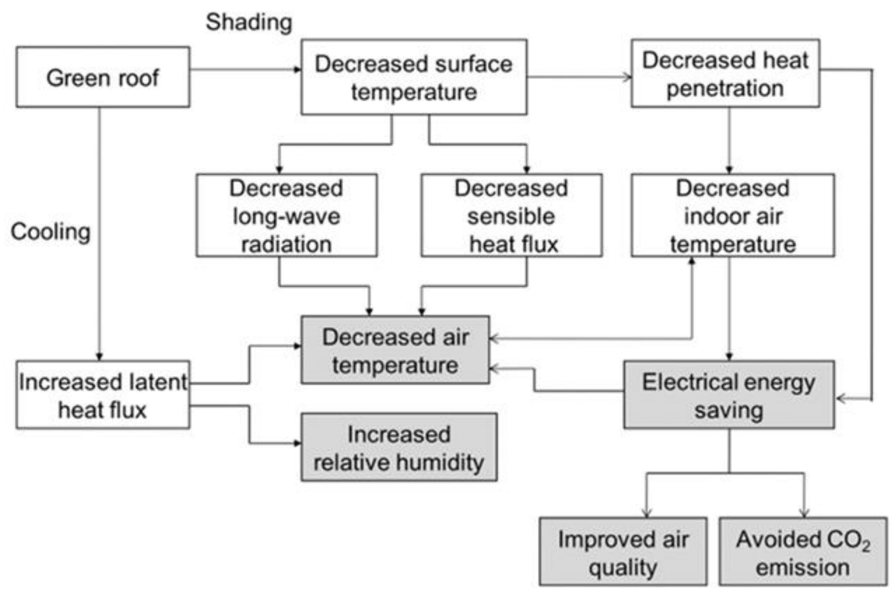

Figure 5. Mechanisms of green-roof thermal effects in summer.
Source: (Peng Lihua 2012).

Green Roofs in the Tropics

One of the most important aspects influencing the implementation of green roofs is the economical one (Vijayaraghavan 2016). This is key when assessing applicability and effectiveness of green roofs. For desired outcomes to become real services, maintenance is a key aspect, and sometimes the cost on the long run can turn unsustainable. Besides cost, there are some other issues that need to be considered before implementing a green roof anywhere: the durability of the structure, the survival rate of the species, the level of dependency, and the type of environment in which it is going to be implemented. Some countries have done economic studies on the long-term return of the inversion and assessments of externalities and marginal gains to assess implementation (Vijayaraghavan 2016). The economical aspect of green roof development and implementation is one of the main constraints in terms of applicability. Researchers have found that, if approached from a public policy level, the popularity and therefore the cost of sustainability initiatives such as the green roofs could be improved and become accessible not only for the organizational level but for the individual as well (Sihau 2008; Peng Lihua 2012; Wong et al. 2003) . One of the main strategies used by states and countries to promote green roofs is the creation of economic incentives (Sihau 2008; Oberndorfer et al. 2007; Olsen 2015). The other one is a mandate by law that all new designs incorporate measurements to achieve sustainability and mitigate urban effects. Some are specific to command the use of green roofs (Oberndorfer et al. 2007; Vijayaraghavan 2016). Most of the time the associated benefits (economical and environmental) of the green roofs are the main justification for the initial investment. Studies have compared the life-cycle expectancy of green roofs to bare roofs, and contrasted the maintenance cost of both roofs. In Singapore a comparative study was performed to evaluate the maintenance cost of both green and flat roofs and as a result the authors highlight that despite the initial cost extensive green roofs are more cost efficient that flat ones. For intensive green roofs the results are more complex since the system requires more attention and specifications (Wong et al. 2003).

In order to maximize their profits, countries have selected and listed the type and species of plants suitable to the environment they face. In an article by (Dvorak and Volder 2013) they state that "in Europe, hundreds of plant species have been identified for use on green roofs" and also "in a recent review of North American green roof vegetation research, 40 succulent species and 94 herbaceous species were identified on green roofs across 15 ecoregions" (Dvorak and Volder 2010). This shows an information gap for the Tropics, regarding species suitability to local conditions and to global tropical climates. In most cases isolated studies have been performed mostly in Asian countries about the effects, design, and survivorship of green roofs but other areas in the Tropics are left behind in terms of these studies and in the delimitation of suitable plants for green roofs in the area.

Most of the articles found in this review about the tropics concern Singapore. This country is well known for the implementation of environmentally friendly strategies to mitigate global climate effects. One of said practices turns out to be the establishment of GRs in large areas of the urbanized country. Studies have been conducted in Singapore concerning the benefits associated with green roofs, studies about runoff quality, UHI effect, other hydrological aspects, etc. (Qin et al. 2012), but few of this studies are focused on plant composition and suitability.

Green Roofs in Puerto Rico

In Puerto Rico as in the rest of the Tropics, the green roof systems has been recently explored and therefore not deeply studied for its broad implementation. In contrast with countries which have taken a public policy approach towards this issue, Puerto Rico has acted sporadically and in individual and small attempts in the implementation of green roofs. Even when there is not a specific set of standards for Puerto Rico, the United States Environmental Protection Agency (EPA), throughout the collection of information from different States implementation strategies, has established guidelines for the cost, design and maintenance of green roofs. Most standards, however, are meant for climatic conditions that differ greatly from those in Puerto Rico, since they are intended for semi-arid or temperate zones. Some specific examples of EPA's green roof guidelines include the "Cost Analysis for the Portland Ecoroof Incentive" (Bureau of Environmental Services 2014) and the "Design Guidelines and Maintenance Manual for Green Roofs in the Semi-Arid and Arid West" (Tolderlund 2010). These last documents even when they have no relationship with Puerto Rico, hold the capacity to be modified and adapted to local conditions maintaining the basic regulatory requirements that are common to all states to be in compliance with federal law.

In Puerto Rico the main focus of researchers has been the quantification of benefits from green roofs, rather than adaptation and application strategies. A study that evaluates possible climate change scenarios on the island of Puerto Rico incorporates a mitigation tool (green roofs) in their data frame to evaluate if the establishment of these green structures can help reduce the effects of the UHI effect, the local temperature increase and some other aspects regarding climate change. As they incorporate GR into their model they show that "green roofs and urban vegetation have a profound effect on the area's air temperature and surface energy balance, producing lower temperatures and storing less energy, partitioning energy as latent heat more efficiently" (Comarazamy et al. 2015). They recommend that green roofs implementation is done at a large scale.

Small, fragmented green roof patches in a much crowded with buildings city would not compensate for the effect of urban issues (Williams, Lundholm, and Scott Macivor 2014; Peng Lihua 2012; Narigon 2013).

Conclusions

What I can conclude from this review is that green roofs possess the capacity to mitigate many of the environmental problems, associated with urban areas. Green roofs can serve to multiple purposes and provide services both for the human welfare and the ecological benefit. They can supply urban areas with green spaces for the recreational, agricultural, aesthetical, and environmental use, providing a large scope of possibilities in terms of design and layout. For their best adaptation and endurance, green roofs need to be design aiming for local suitability. Both soil and plant species selection should be consider under the scope of local condition adequacy. European countries and other temperate zones have advanced the topic and have improved the design through decades of research; the same should be done in countries in the tropical region following Singapore's pioneering example.

Acknowledgements

I would like to acknowledge my committee members for their positive feedback and constructive comments during the witting process. I would also like to thank Snejanka Penkova for her help in the literature search and examination.

References

Berardi, Umberto, AmirHosein GhaffarianHoseini, and Ali GhaffarianHoseini. 2014. "State-of-the-Art Analysis of the Environmental Benefits of Green Roofs." *Applied Energy* 115 (February): 411–28. doi:10.1016/j.apenergy.2013.10.047.

Bolaños-Silva, Tomás, and Andrés Moscoso-Hurtado. 2011. "Consideraciones Y Selección de Especies Vegetales Para Su Implementación En Ecoenvolventes Arquitectónicos : Una Herramienta Metodológica." *Revista Nodo* 5: 5–20. https://dialnet.unirioja.es/servlet/articulo?codigo=3736189.

Bozorg Chenani, Sanaz, Susanna Lehvävirta, and Tarja Häkkinen. 2014. "Life Cycle Assessment of Layers of Green Roofs." *Journal of Cleaner Production* 90 (December): 153–62. doi:10.1016/j.jclepro.2014.11.070.

Bureau of Environmental Services, City of Portland. 2014. "Cost Analysis for the Portland Ecoroof Incentive." Portland.

Comarazamy, Daniel E., Jorge E. González, and Jeffrey C. Luvall. 2015. "Quantification and Mitigation of Long-Term Impacts of Urbanization and Climate Change in the Tropical Coastal City of San Juan, Puerto Rico." *International Journal of Low-Carbon Technologies* 10 (1): 87–97. doi:10.1093/ijlct/ctt059.

Cuerda, I, B Rivela, C Gazulla, F Olivieri, C Bedoya, and J Neila. 2000. "Environmental Profile of Green Roof Material in Different Locations in Spain : Life Cycle Assessment and Optimisation ." http://oa.upm.es/7448/1/INVE_MEM_2010_76255.pdf.

Dvorak, Bruce D., and Astrid Volder. 2013. “Plant Establishment on Unirrigated Green Roof Modules in a Subtropical Climate.” *AoB PLANTS* 5. doi:10.1093/aobpla/pls049.

Dvorak, Bruce, and Astrid Volder. 2010. “Green Roof Vegetation for North American Ecoregions: A Literature Review.” *Landscape and Urban Planning* 96 (4): 197–213. http://www.sciencedirect.com/science/article/pii/S0169204610000782.

Gargari, Caterina, Carlo Bibbiani, Fabio Fantozzi, and Carlo Alberto Campiotti. 2016. “Environmental Impact of Green Roofing: The Contribute of a Green Roof to the Sustainable Use of Natural Resources in a Life Cycle Approach.” *Agriculture and Agricultural Science Procedia* 8: 646–56. doi:10.1016/j.aaspro.2016.02.087.

He, Chunyang, Da Zhang, Qingxu Huang, and Yuanyuan Zhao. 2016. “Assessing the Potential Impacts of Urban Expansion on Regional Carbon Storage by Linking the LUSD-Urban and InVEST Models.” *Environmental Modelling & Software* 75 (January): 44–58. http://www.sciencedirect.com/science/article/pii/S136481521530058X.

Jim, C.Y. 2015. “Assessing Climate-Adaptation Effect of Extensive Tropical Green Roofs in Cities.” *Landscape and Urban Planning* 138 (March): 54–70. http://www.sciencedirect.com/science/article/pii/S0169204615000456.

Karteris, Marinos, Ifigeneia Theodoridou, Giorgos Mallinis, Emmanouel Tsiros, and Apostolos Karteris. 2016. “Towards a Green Sustainable Strategy for Mediterranean Cities: Assessing the Benefits of Large-Scale Green Roofs Implementation in Thessaloniki, Northern Greece, Using Environmental Modelling, GIS and Very

High Spatial Resolution Remote Sensing Data." *Renewable and Sustainable Energy Reviews* 58 (May): 510–25. doi:10.1016/j.rser.2015.11.098.

Li, Yanling, and Roger W. Babcock. 2014. "Green Roofs against Pollution and Climate Change. A Review." *Agronomy for Sustainable Development* 34 (4): 695–705. doi:10.1007/s13593-014-0230-9.

Lugo, Ariel E, and Jeannette Rullán. 2015. "The Conservation Message of the Rehabilitated Facilities of the International Institute of Tropical Forestry," no. November.

Malcolm, Elizabeth G., Margaret L. Reese, Maynard H. Schaus, Ivy M. Ozmon, and Lan M. Tran. 2014. "Measurements of Nutrients and Mercury in Green Roof and Gravel Roof Runoff." *Ecological Engineering* 73 (December): 705–12. http://www.sciencedirect.com/science/article/pii/S0925857414004418.

Nagase, Ayako, and Nigel Dunnett. 2012. "Amount of Water Runoff from Different Vegetation Types on Extensive Green Roofs: Effects of Plant Species, Diversity and Plant Structure." *Landscape and Urban Planning* 104 (3–4): 356–63. http://www.sciencedirect.com/science/article/pii/S0169204611003239.

Narigon, Henry. 2013. "Green Roof Biodiversity in Design : Influence of Local and Contextual Attributes on Bird Usage." Iowa State University. http://lib.dr.iastate.edu/cgi/viewcontent.cgi?article=4608&context=etd.

Oberndorfer, Erica, Jeremy Lundholm, Brad Bass, Reid R. Coffman, Hitesh Doshi, Nigel Dunnett, Stuart Gaffin, Manfred Köhler, Karen K. Y. Liu, and Bradley Rowe. 2007. "Green Roofs as Urban Ecosystems: Ecological Structures, Functions, and

Services.” *BioScience* 57 (10): 823. doi:10.1641/B571005.

Olsen, Kerby. 2015. “EVALUATING URBAN DESIGN STRATEGIES FOR CLIMATE CHANGE by.” California Polytechnic State University, San Luis Obispo. http://digitalcommons.calpoly.edu/cgi/viewcontent.cgi?article=2490&context=theses.

Ondoño, S., J.J. Martínez-Sánchez, and J.L. Moreno. 2015. “Evaluating the Growth of Several Mediterranean Endemic Species in Artificial Substrates: Are These Species Suitable for Their Future Use in Green Roofs?” *Ecological Engineering* 81 (August): 405–17. doi:10.1016/j.ecoleng.2015.04.079.

Parnell, Susan. 2016. “Defining a Global Urban Development Agenda.” *World Development* 78 (February): 529–40. http://www.sciencedirect.com/science/article/pii/S0305750X15002508.

Peng Lihua, Lilliana. 2012. “Green-Roof Thermal Effects in the Context of Climate Change and.” University of Hong Kong. http://hub.hku.hk/bitstream/10722/181517/1/FullText.pdf?accept=1.

Ponni, M, and R Baskar. 2015. “Comparative Study of Different Types of Roof and Indoor Temperatures in Tropical Climate.” *International Journal of Engineering and Technology (IJET)* 7 (2): 530–36. http://www.enggjournals.com/ijet/docs/IJET15-07-02-315.pdf.

Qin, X, X Wu, Y-M Chiew, and Y Li. 2012. “A Green Roof Test Bed for Stormwater Management and Reduction of Urban Heat Island Effect in Singapore.” *British*

Journal of Environment and Climate Change 2 (4): 410–20. http://bf4dv7zn3u.search.serialssolutions.com.myaccess.library.utoronto.ca/?ctx_ver=Z39.88-2004&ctx_enc=info:ofi/enc:UTF-8&rfr_id=info:sid/ProQ%25253Apqrl&rft_val_fmt=info:ofi/fmt:kev:mtx:journal&rft.genre=article&rft.jtitle=British+Journal+of+Environment+a.

Razzaghmanesh, Mostafa, Simon Beecham, and Telma Salemi. 2016. “The Role of Green Roofs in Mitigating Urban Heat Island Effects in the Metropolitan Area of Adelaide, South Australia.” *Urban Forestry & Urban Greening* 15: 89–102. doi:10.1016/j.ufug.2015.11.013.

Romnée, Ambroise, Arnaud Evrard, and Sophie Trachte. 2015. “Methodology for a Stormwater Sensitive Urban Watershed Design.” *Journal of Hydrology* 530 (November): 87–102. http://www.sciencedirect.com/science/article/pii/S0022169415007374.

Saadatian, Omidreza, K. Sopian, E. Salleh, C.H. Lim, Safa Riffat, Elham Saadatian, Arash Toudeshki, and M.Y. Sulaiman. 2013. “A Review of Energy Aspects of Green Roofs.” *Renewable and Sustainable Energy Reviews* 23 (July): 155–68. http://www.sciencedirect.com/science/article/pii/S136403211300124X.

Sihau, Lindsey. 2008. “Green Roofs for a Green Town : Possibilities of Green Roof Implementation in the Town of Normal.” http://digitalcommons.iwu.edu/cgi/viewcontent.cgi?article=1005&context=envstu_seminar.

Speak, Andrew Francis. 2013. “Quantification of the Environmental Impacts of Urban

Green Roofs.” https://www.escholar.manchester.ac.uk/api/datastream?publicationPid=uk-ac-man-scw:203993&datastreamId=FULL-TEXT.PDF.

Srivastava, Rohini. 2011. “Green Roof Design and Practices :” Kent State University. https://etd.ohiolink.edu/ap:10:0::NO:10:P10_ACCESSION_NUM:kent1311004642.

Teemusk, Alar, and Ülo Mander. 2007. “Rainwater Runoff Quantity and Quality Performance from a Greenroof: The Effects of Short-Term Events.” *Ecological Engineering* 30 (3): 271–77. http://www.sciencedirect.com/science/article/pii/S0925857407000134.

Tolderlund, Leila. 2010. “Design Guidelines and Maintenance Manual for Green Roofs in the Semi-Arid and Arid West.” *Environment And Behavior,* 59. http://www.epa.gov/region8/greenroof/pdf/GreenRoofsSemiAridAridWest.pdf.

Van Mechelen, Carmen, Thierry Dutoit, and Martin Hermy. 2015. “Vegetation Development on Different Extensive Green Roof Types in a Mediterranean and Temperate Maritime Climate.” *Ecological Engineering* 82. Elsevier B.V.: 571–82. doi:10.1016/j.ecoleng.2015.05.011.

Van Mechelen, Carmen, Koenraad Van Meerbeek, Thierry Dutoit, and Martin Hermy. 2015. “Functional Diversity as a Framework for Novel Ecosystem Design: The Example of Extensive Green Roofs.” *Landscape and Urban Planning* 136 (April): 165–73. doi:10.1016/j.landurbplan.2014.11.022.

Van Renterghem, Timothy, and Dick Botteldooren. 2011. “In-Situ Measurements of Sound Propagating over Extensive Green Roofs.” *Building and Environment* 46 (3):

729–38. http://www.sciencedirect.com/science/article/pii/S0360132310002982.

Vijayaraghavan, K. 2016. “Green Roofs: A Critical Review on the Role of Components, Benefits, Limitations and Trends.” *Renewable and Sustainable Energy Reviews* 57 (May): 740–52. doi:10.1016/j.rser.2015.12.119.

Vijayaraghavan, K, and Umid Man Joshi. 2014. “Can Green Roof Act as a Sink for Contaminants? A Methodological Study to Evaluate Runoff Quality from Green Roofs.” *Environmental Pollution (Barking, Essex : 1987)* 194 (November): 121–29. doi:10.1016/j.envpol.2014.07.021.

Williams, Nicholas S G, Jeremy Lundholm, and J. Scott Macivor. 2014. “Do Green Roofs Help Urban Biodiversity Conservation?” *Journal of Applied Ecology* 51 (6): 1643–49. doi:10.1111/1365-2664.12333.

Wong, Nyuk Hien, Su Fen Tay, Raymond Wong, Chui Leng Ong, and Angelia Sia. 2003. “Life Cycle Cost Analysis of Rooftop Gardens in Singapore.” *Building and Environment* 38 (3): 499–509. doi:10.1016/S0360-1323(02)00131-2.

CHAPTER 2. Vegetation dynamics of tropical green roofs, study from four extensive green roofs in San Juan, Puerto Rico

Abstract

Green roofs are a proposed strategy for urban sustainability and involve multiple environmental, ecological, and social benefits. The applicability of green roofs has been vaguely explored in terms of ecosystem dynamics in tropical regions and there is no available list of species that could be used in a tropical setting. This study is a descriptive analysis of suitable species for their possible incorporation in green roof designs with tropical climate conditions. The evaluation of the vegetation dynamics in these novel ecosystems was done through a case study in the recently renewed facilities of the International Institute of Tropical Forestry (IITF) in Río Piedras, Puerto Rico, which incorporated a set of green roofs in their infrastructure. We also sampled an older green roof built in the Social Sciences Faculty at the University of Puerto Rico at Río Piedras. A three-dimensional approach, the Point-Intercept Method, was taken in the vegetation surveys in order to capture as much as possible the green infrastructure of the roofs. Most of the originally planted species did not appear in these surveys. On the contrary, mainly newly species dominated the areas. Along with the findings of these surveys and those in other tropical countries lists, a list of suitable species for green roofs in Puerto Rico is suggested.

Key words: Green roofs – vegetation dynamics – species composition – green roof ecosystems

Introduction

Green roofs (GR) are vegetated spaces on top of buildings installed within a city in order to enhance their greenery (Vijayaraghavan 2016; Dvorak and Volder 2010; Kamarulzaman et al. 2014). GRs serve as both mitigation and remediation tools for many of the problems related to urban areas, such as decrease in green spaces (Vijayaraghavan 2016), air contamination (Li and Babcock 2014), storm water degradation (Razzaghmanesh, Beecham, and Salemi 2016), among others.

Green roofs have become popular in the most recent decades as part of integrated strategies by countries as an approach to achieve sustainability (Li and Babcock 2014; Saadatian et al. 2013; Parnell 2016). Some argue that GR have been around for a little longer than that, recalling the Hanging Gardens of Babylon as one of the first examples of GR implementation (Vijayaraghavan 2016; Berardi, GhaffarianHoseini, and GhaffarianHoseini 2014; Srivastava 2011; Santana 2016). Green roofs have served for multiple uses at both the individual and organizational levels (Srivastava 2011), providing areas for agricultural activities, recreational spaces, ecological services, and merely as aesthetical enhancers. The design, complexity and success of these novel ecosystems have been the subject of numerous investigations describing the most suitable elements to be incorporated, like the substrate or growth media mixture and balance, the list of plant species, the layers material and composition, etc.

Regardless of the time green roofs have been around and the studies conducted to learn their performance, little is known about the success of this ecological units in tropical environments (Lugo and Rullán 2015; Jean et al. 2014; Santana 2016). The tropical region contains a great amount of the world biodiversity and counts with a different climatic condition than that on the temperate zone. For this reason a careful evaluation needs to be done to measure how to adapt the design to the climatic features of tropical zones. Most of the information about the design and suitable characteristics are from climates that have very distinct seasonality and the range of temperatures and humidity differ from those on the tropical region greatly (Dvorak and Volder 2010). Precipitation amounts are one of the most important considerations for the design, given that the retention of excess water could translate into undesired saturated conditions for the ecological component, and as extra weight of the system for the structural perspective.

Puerto Rico as an island located in the Caribbean has the climatic characteristics and features of much of the tropics. It comprises an area of 8740 km^2 that receives 400-8,000 mm yr^{-1} of rainfall among its life zones (Muscarella et al. 2016). As a territory of the United States of America, many standards and policies in the Island as written for the mainland USA also apply to Puerto Rico (Rudel, Perez-Lugo, and Zichal 2000). Puerto Rico has started to implement, from individually stimulated efforts, green roof technology. A comprehensive list of green roofs in the island is lacking, but buildings such as the Cuartel de Ballajá, Music Conservatory, Banco Popular Tower, the International Institute of Tropical Forestry (IITF), and the Social Sciences Faculty of the UPR-RP[1], among other sites, have already installed green roofs.

The research performed to evaluate the performance and adaptability of the green roofs in Puerto Rico are scarce and ultimately address the benefits to be obtained by said structure rather that its accommodation to the local conditions. Comarazamy et al. (2015)

[1] UPR-RP: University of Puerto Rico, Río Piedras Campus

evaluated, for instance, the impact of the modeled establishment of green roofs in a large scale in the coastal city of San Juan undergoing the impacts of climate change. But the study did not evaluated the implementation process of GR. IITF performed a study evaluating runoff quality and its effect on the urban stream of Río Piedras (Lugo and Rullán 2015) but addressed little regarding the compliance of the design with the local conditions. In particular, the choice of species for planting on green roofs was not addressed.

Vegetation analysis has not being performed yet to evaluate the species that have best survival rates in Puerto Rico. In order to offer a descriptive analysis of vegetation dynamics of green roofs in a tropical setting, this case study incorporates a vegetation survey that sheds light over the current conditions of the roofs as a potential platform for future investigations on the topic that ultimately could serve as a thorough list of species for tropical green roof design. For that purpose the following questions where established.

1. *How does original species list and current surveyed species compare?*
2. *What were the most dense and frequent species among green roof depths?*
3. *What set of species is more suitable for their incorporation on green roof design in tropical environmental conditions?*

Methods

Study Site

The case study of vegetation dynamics of tropical green roofs was done in the recently renewed facilities of the International Institute of Tropical Forestry (IITF) in San Juan, Puerto Rico. The IITF, located in the Botanical Garden of the University of Puerto Rico within the San Juan City, has five buildings. Green roofs were installed on four of them: the GIS and Remote Sensing Laboratory, Chemistry Laboratory Annex, Technology Transfer Conference Center, and a Multipurpose Building (Lugo and Rullán 2015, Fig. 1). The renovation of the facilities was done through a process that lasted almost 20 years and had the main purpose of bringing to the buildings and facilities the mission and vision of the Forest Service, and the LEED[2] certification. On May 22nd, 2013 that the employees of the Institute formally inaugurated their green roofs (Lugo and Rullán 2015).

The layout and design of the GR was intended for experimentation on the benefits of green roofs. The GIS and Multipurpose buildings were sub-divided into seven (7) separate green roofs and one (1) cool roof. Soil depths were varied in each GR sub-division (5.08cm, 7.62cm, 10.16cm, 12.7cm, 15.24cm, 20.32cm, & 25.4cm) (Table 1).

[2] LEED: Leadership in Energy and Environmental Design.

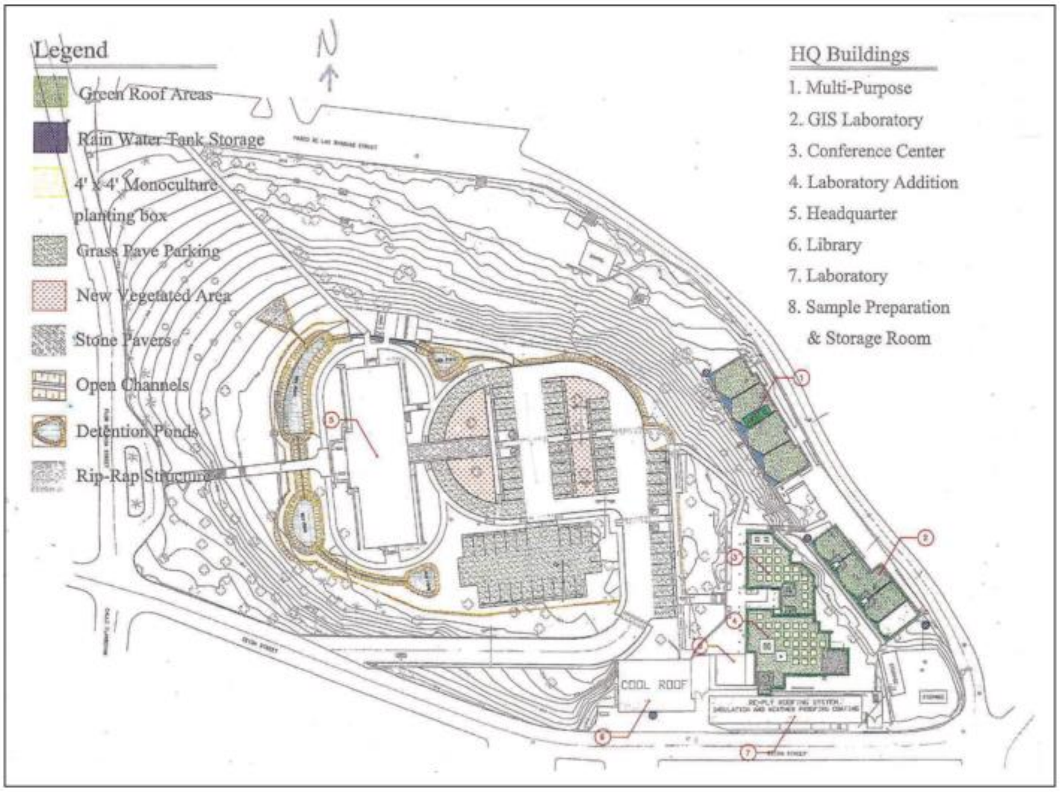

Figure 1. Spatial distribution of current building facilities, green parking lot, and green roofs at the headquarters of the International Institute of Tropical Forestry. (Lugo and Rullán 2015)

Buildings at the IITF that did not incorporate the division scheme for future research were treated the same way and plant composition was similar to the other ones. All green roofs were previous cool roofs as described by Lugo and Rullán (2015) in an article that explains the conceptualization and intention of the renovation of the IITF facilities. The layers incorporated in the design as well as their specifications are summarized in Table 2 & 3.

Table 1. Green Roofs identification and description.

Building Location	Building Owner	Building Purpose	Roof Number	Green Roof Depths	Transects Numbers
Botanical Garden of San Juan, P.R.	IITF	GIS Laboratory	1	cool roof 5.08 cm 7.62 cm 10.16 cm	--- 7-9 4-6 1-3
Botanical Garden of San Juan, P.R.	IITF	Chemistry Laboratory & Conference Room	2	10.16 cm	10-18
Botanical Garden of San Juan, P.R	IITF	Multipurpose	3	12.7 cm 15.24 cm 20.32 cm 25.4 cm	28-30 25-27 22-24 19-21
University of Puerto Rico, Rio Piedras	UPR	Social Sciences Faculty	4	N/A[3]	31-36

The green roofs installed at the IITF facilities are extensive ones (Berardi, GhaffarianHoseini, and GhaffarianHoseini 2014) , with a variety of depths. A total of 26 species were originally planted (around 16,000 plugs were installed on the project, with some seeds) (Table 4). Maintenance has been minimum throughout the years, which has allowed spontaneous vegetation to colonize the areas and original planted species have either diminished in coverage or disappeared; occasional tree growth can be seen as well. As part of the plan of providing a study site for future investigations the roofs count with various sensors that monitor three major aspects to be evaluated on them: balances of energy, water, and nutrients. Hobo weather stations were placed on the rooftops to monitor air temperature, humidity, wind speed, impact energy, and rain. All sub-divisions can be monitored for thermal and storm water behavior as well.

[3] N/A: Not available Information

Table 2. List of attributes provided by the contractor from the IITF green roof installation.

Layer Material Description			
Water Proofing	Ethylene Propylene Diene Terpolymer (EPDN) membrane.	2.29 mm	
Root Barrier	ZinCo WSF 40	Thickness: 50.8 mm	Weight: 4.88 kg/m^2
Moisture Retention Mat	ZinCo SSM 45	Thickness: 50.8 mm	WRC[4]: 488.95 L/m^2
Drainage Board	Floradrain FD 40-E	Weight: 24.41 kg/m^2	WRC: 40.74 L/m^2
Filter Fabric	Zinco SF	WFR[5]: 9290.05 L/m2	Weight: 9.76 kg/m^2

An additional green roof on the UPR – Río Piedras campus was also incorporated into this case study. This one stands above the Social Sciences Faculty's building and is more than 20 years old. The design and structure differs from modern green roofs but since it does not receive any maintained either it serves as a good platform for spontaneous vegetation studies. Dr. Carlos Severino (personal communication) informed us that by the beginning there were only two species involved in the design, *Kalanchoe tubiflora* y *Kalanchoe daigremontiana*.

[4] WRC: Water Retention Capacity given by the manufacturer.
[5] WFR: Water Flow Rate given by the manufacturer

Table 3. Growing medium description provided by the contractor from the IITF green roof installation.

Particle Size Distribution	
Proportion of silting components	d< 0.063 mm (Mass % ≤ 10)
Density Measurements	
Bulk Density (dry weight basis)	0.55 – 0.80 g/cm
Bulk Density (at max. water holding capacity)	1.05 – 1.15 g/cm
Water/Air Measurements	
Total pore volume	70 ≤ Vol. %
Maximum water holding capacity (MWHC)	35-65 Vol. %
Air-filled porosity at MWHC	10 ≤ Vol. %
Water permeability (saturated hydraulic conductivity)	0.001 – 0.12 cm/sec
pH and Salt Content	
pH (in $CaCl_2$)	6.0 – 8.5
Soluble salts (water extract)	< 3.5 g/L
Soluble salts (gypsum extract)	< 2.5 g/L
Organic Measurements	
Organic matter content	<65 g/L
Nutrients	
Phosphorus P205 (CAL)	< 200 mg/L
Potassium K_2O (CAL)	< 700 mg/L
Magnesium Mg ($CaCl_2$)	< 200 mg/L
Nitrate + Ammonium ($CaCl_2$)	< 80 mg/L

Table 4. List of species planted as part of the original design at the green roofs of the International Institute of Tropical Forestry (IITF).

No.	Species Name	Assigned Species Code
1	*Agapanthus praecox*	AGA PRA
2	*Aloe barbadensis*	ALO VER
3	*Aptenia cordifolia*	APT COR
4	*Arachis hypogaea*	ARA HYP
5	*Capobrotus edulis*	CAP EDU
6	*Crassula muscosa*	CRA MUS
7	*Cymbopogon ambiguus*	CYM AMB
8	*Delosperma sutherlandii*	DEL SUT
9	*Lamprantus deltoids*	LAM DEL
10	*Malephora crocera*	MAL CRO
11	*Malephora lutea*	MAL LUT
12	*Passiflora foetida*	PAS FOE
13	*Penstemon pinifolus*	PEN PIN
14	*Rhoeo spathacea*	RHO SPA
15	*Rosmarinus officinalis*	ROS OFF
16	*Ruschia pulminaris*	RUS PUL
17	*Sansevieria cylindrica*	SAN CYL
18	*Sansevieria hahnii*	SAN HAH
19	*Sedum dasyphyllum*	SED DAS
20	*Sedum mexicanum*	SED MEX
21	*Sedum pulchellum*	SED PUL
22	*Sedum rubrotinctum*	SED RUB
23	*Sedum stahlii*	SED STA
24	*Stapelia grandiflora*	STA GRAN
25	*Talinum paniculatum*	TAL PAN
26	*Tulbaghia violacea*	TUL VIO

Vegetation surveys.

Green roofs were identified with numbers following the order at which they were sampled, mainly dictated by accessibility. All roofs were sampled from north to south and the identification of transects was done in the same manner using a random number generator to locate them. The ends of transects were permanently marked for future surveys and a long term evaluation of the vegetation of the green roofs.

To determine the abundance of herbaceous species on green roofs, we used the Point-Intercept Method as descibed by Mueller-Dombois & Ellenberg (1974). This method samples the three dimensional layout of plant structure by counting the number of "touches" by pins lowered through the vegetation every 20 cm. It is a nondestructive measure of plant abundance that avoids the subjectivity of visual cover estimates. A 1 meter frame (Fig. 2) with ten pins was placed every 20cm along 3 different transects (per depth) placed randomly along each roof (Fig. 3-6); for the second and fourth roofs since there was no variation in the substrate depths 9 and 6 transects were survey respectively. Transects were 7 meters long on the roofs 1, 2 and 3. Because of roof size and shape for the 4th GR, at the Social Sciences Faculty the length was increased to 14m.

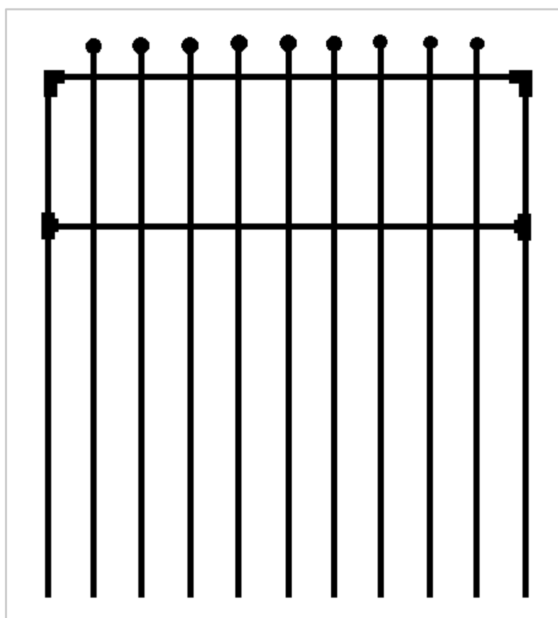

Figure 2. Vegetation sampling frame sketch modified from the Point- Intercept Method.

Counts of touches were aggregated by 1x1 m quadrats. The abundance of each species was summarized by the sum of touches per species over all touches (relative density) and presence vs. absence in 1-m^2 quadrats over the sum of the number of quadrats (relative frequency). This values helped distinguish the most abundant versus widespread (but sparsely vegetated) species. Lastly an Importance Value (IV) was calculate for each species by summing relative density and relative frequency.

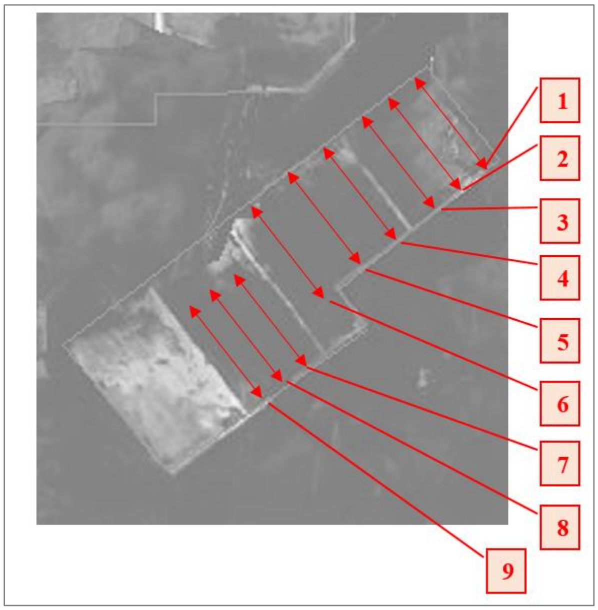

Figure 3. Green roof # 1 (GIS Laboratory) at the International Institute of Tropical Forestry and transects identification and location.

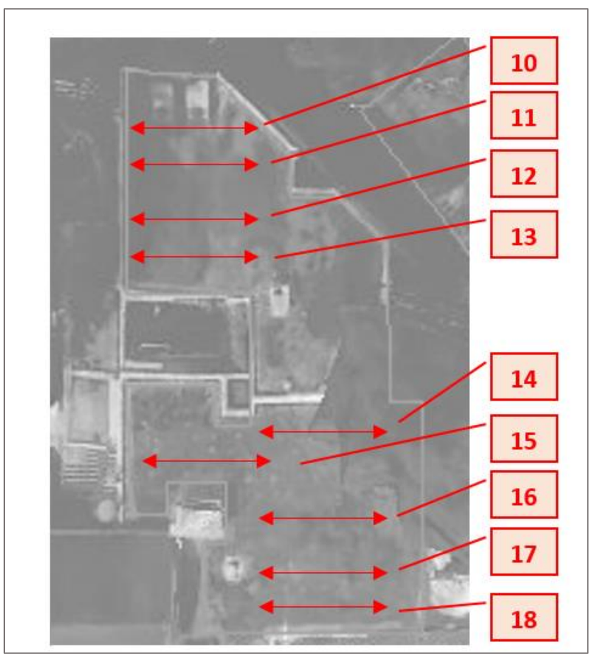

Figure 4. Green roof # 2 (Chemistry Laboratory and Conference Room) at the International Institute of Tropical Forestry and transects identification and location.

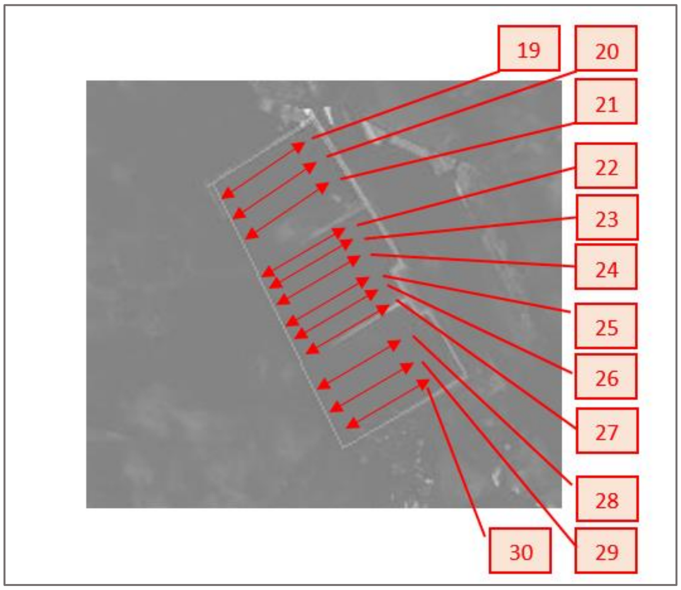

Figure 5. Green roof # 3 (Multipurpose Building) at the International Institute of Tropical Forestry and transects identification and location.

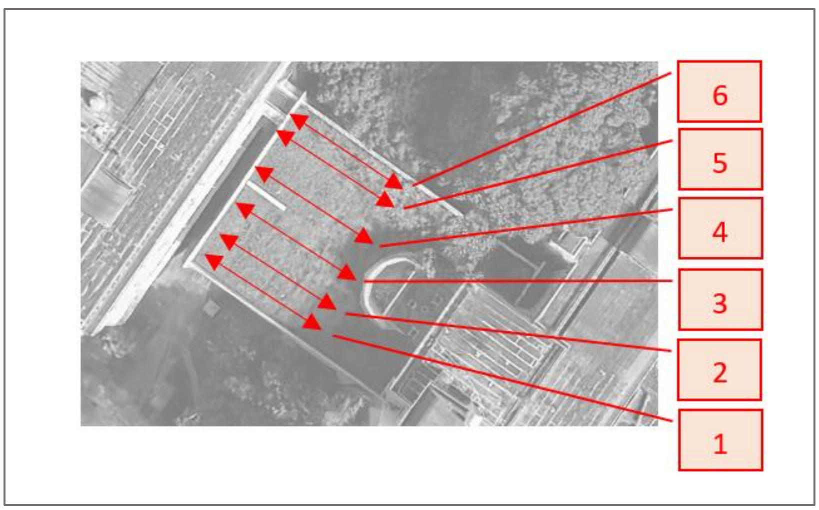

Figure 6. Green roof # 4 at the Social Sciences Faculty in the University of Puerto Rico at Rio Piedras Campus and transects identification and location.

Results

After performing the vegetation surveys we found a constant set of species that appears in almost all roof depths and species that are specific to substrate thickness. Few of the originally planted species, showed up in the surveys. The first sampled green roof (Roof # 1) in all its subdivisions (5.08, 7.62, 10.16 cm) the most dominant species was *Bidens alba*, ranking first not only in importance value (156.78, 132.43, and 148.89, respective to the depths) but in its relative density (56.78 %, 37.20 %, 48.89 %) and relative frequency (100 %, 95.24 %, 100 %) (Tables 5-7). Other species were frequent but not as dense, such as *Tulbaghia violacea*, *Arachis hypogaea*, and *Alopecurus pratensis*, with Importance Values in all three depths respectively (61.93, 102.65, and 96.42) due to their high relative frequency (52.38 %, 85.71 %, 76.19 %) but not their relative density (9.55 %, 16.94 %, 20.23%). Species that appeared in all depths were *Cyperaceae kyllinga*, *Portulaca grandiflora*, *Asclepias curassavica*, and *Paspalum paniculatum*. *Asclepias curassavica* was not part of the originally planted set of species, but used as part of an IITF project to attract monarch butterflies (*Danaus plexippus*).

Table 5. Summary of vegetation analysis of the Green Roof # 1 at the 5.08cm depth.

Species Code	Species Name	Relative Density (%)	Relative Frequency (%)	Importance Value
BID ALB	*Bidens alba*	56.78	100.00	156.78
TUL VIO	*Tulbaghia violacea*	9.55	52.38	61.93
NEP MUL	*Nephrolepis multiflora*	23.67	38.10	61.77
CYP KYL	*Cyperaceae kyllinga*	7.48	52.38	59.86
POR GRA	*Portulaca grandiflora*	0.67	19.05	19.72
BUL CAU	*Bulbine caulescens*	1.68	4.76	6.44
ASC CUR	*Asclepias curassavica*	0.06	4.76	4.82
EMI FOS	*Emilia fosbergii*	0.06	4.76	4.82
PAS GRA	*Paspalum paniculatum*	0.06	4.76	4.82

Table 6. Summary of vegetation analysis of the Green Roof # 1 at the 7.62cm depth.

Species Code	Species Name	Relative Density (%)	Relative Frequency (%)	Importance Value
BID ALB	*Bidens alba*	37.20	95.24	132.43
ARA HYP	*Arachis hypogaea*	16.94	85.71	102.65
NEP MUL	*Nephrolepis multiflora*	34.48	38.10	72.58
MOM CHA	*Momordica charantia*	6.24	52.38	58.62
ASC CUR	*Asclepias curassavica*	0.08	9.52	9.60
CYP KYL	*Cyperaceae kyllinga*	1.01	33.33	34.35
TUL VIO	*Tulbaghia violacea*	2.03	23.81	25.84
POR GRA	*Portulaca grandiflora*	1.30	19.05	20.34
PAS GRA	*Paspalum paniculatum*	0.57	14.29	14.85
OXA ART	*Oxalis articulata*	0.12	9.52	9.65
SED STA	*Sedum Stahlii*	0.04	4.76	4.80

Table 7. Summary of vegetation analysis of the Green Roof # 1 at the 10.16cm depth.

Species Code	Species Name	Relative Density (%)	Relative Frequency (%)	Importance Value
BID ALB	*Bidens alba*	48.89	100.00	148.89
FOX GRA	*Alopecurus pratensis*	20.23	76.19	96.42
ARA HYP	*Arachis hypogaea*	10.79	42.86	53.65
TUL VIO	*Tulbaghia violacea*	9.79	38.10	47.89
ASC CUR	*Asclepias curassavica*	1.86	38.10	39.95
POR OLE	*Portulaca oleracea*	1.72	33.33	35.05
PUR FLO	*Stachytarpheta jamaicensis*	3.07	14.29	17.36
MOM CHA	*Momordica charantia*	0.86	14.29	15.14
POR GRA	*Portulaca grandiflora*	0.79	14.29	15.07
EMI FOS	*Emilia fosbergii*	0.71	14.29	15.00
PAS GRA	*Paspalum paniculatum*	0.36	14.29	14.64
OXA ART	*Oxalis articulata*	0.29	9.52	9.81
UNK THU	*Unknown Thunbergia spp*	0.50	4.76	5.26
CYP KYL	*Cyperaceae kyllinga*	0.07	4.76	4.83
EMI SON	*Emilia sonchifolia*	0.07	4.76	4.83

The GR # 2 (Table 8), that counts with a substrate depth of 10.16 cm, showed a similar pattern as the first sampled roof; again *Bidens alba* was the most dominant species (IV[6]: 131.93, RD[7]: 39.86%, RF[8]: 92.06%). *Arachis hypogaea* was the second in IV (65.43) with a relative density of 30.51 % and relative frequency of 34.92 %. The third most important species was one that did not appear before, *Passiflora foetida*; this species was present in 2 of the three roofs sampled at the IITF, but more abundant in the GR # 2. In this roof there were two species that were only present within this area, e.g., *Macroptilium lathyroides* (IV: 18.10, RD: 0.55%, RF: 17.46%) and *Portulacaria afra* (IV: 1.61, RD: 0.02%, RF: 1.59%).

Table 8. Summary of vegetation analysis of the Green Roof # 2.

Species Code	Species Name	Relative Density (%)	Relative Frequency (%)	Importance Value
BID ALB	*Bidens alba*	39.86	92.06	131.93
ARA HYP	*Arachis hypogaea*	30.51	34.92	65.43
PAS FOE	*Passiflora foetida*	3.72	31.75	35.47
NEP MUL	*Nephrolepis multiflora*	13.68	14.29	27.96
PAS GRA	*Paspalum paniculatum*	1.93	22.22	24.15
BUL CAU	*Bulbine caulescens*	4.25	17.46	21.71
TUL VIO	*Tulbaghia violacea*	3.75	14.29	18.03
MAC LAT	*Macroptilium lathyroides*	0.55	17.46	18.01
OXA COR	*Oxalis corniculata*	0.87	9.52	10.40
MOM CHA	*Momordica charantia*	0.21	6.35	6.56
ASC CUR	*Asclepias curassavica*	0.14	4.76	4.90
POR PIL	*Portulaca pilosa*	0.32	3.17	3.50
POR GRA	*Portulaca grandiflora*	0.07	3.17	3.24
CYP KYL	*Cyperaceae kyllinga*	0.09	1.59	1.68
FOX GRA	*Alopecurus pratensis*	0.02	1.59	1.61
POR AFR	*Portulacaria afra*	0.02	1.59	1.61

[6] IV: Importance Value
[7] RD: Relative Density
[8] RF: Relative Frequency

Green roof # 3, as described before is also subdivided in different substrate depths (12.7, 15.24, 20.32, and 25.4 cm) but the dynamics were very different for each of the sections and there was not a clear trend of dominance in this roof. The first subdivision with 12.7cm substrate (Table 9) had a composition similar to the roofs sampled before. *Bidens alba* remaining the most dominant species with the following values: IV: 124.25, RD: 24.45%, RF: 100%. *Momordica charantia* was also common in this subdivision, ranking second (IV: 118.47, RD: 23.23%, RF: 95.24%). This species, even when present in the first two GR, was not as dense or frequent. A set of species specific to this section were *Spermacoce verticilata* and *Talinum paniculatum*.

Table 9. Summary of vegetation analysis of the Green Roof # 3 at 12.7cm depth.

Species Code	Species Name	Relative Density (%)	Relative Frequency (%)	Importance Value
BID ALB	*Bidens alba*	24.45	100.00	124.45
MOM CHA	*Momordica charantia*	23.23	95.24	118.47
UNK THU	*Unknown Thunbergia spp*	12.22	90.48	102.70
PAS GRA	*Paspalum paniculatum*	18.68	76.19	94.87
CYP KYL	*Cyperaceae kyllinga*	8.73	71.43	80.16
ASC CUR	*Asclepias curassavica*	1.82	57.14	58.97
UNK IPO	*Unknown Ipomea spp*	6.53	42.86	49.39
EUP GRA	*Euphorbia graminea*	1.97	38.10	40.07
SPE VER	*Spermacoce verticilata*	0.91	23.81	24.72
OXA CUR	*Oxalis corniculata*	0.23	14.29	14.51
EMI FOS	*Emilia fosbergii*	0.84	9.52	10.36
UNK DES	*Unknown Desmodium spp*	0.30	4.76	5.07
TAL PAN	*Talinum paniculatum*	0.08	4.76	4.84

Is in the third roof at a depth of 15.24cm (Table 10) a different species showed dominance over the *Bidens alba*. *Unknown Thunbergia spp* ranked first in Importance Value (122.06), with a relative density of 26.82%, and a relative frequency of 95.24%.

Momordica charantia remained in second place for this subdivision, (IV: 118.27, RD: 23.03%, RF: 95.24%). There were no species specific to this section and the composition was similar to the surrounding areas. Similarly on the 20.32 cm deep green roof section (Table 11) there were not many site-specific species, only *Cissus verticilata* (IV: 4.82, RD: 0.05%, RF: 4.76%). In this section what was more abundant was *Unknown Ipomea spp*, (IV: 150.83, RD: 50.83%, RF: 100%). This species was present only in this roof but in three out of four of its sections. The last section, and the deepest among all green roofs (25.4cm) described at Table 12, contained species already sampled in previous roofs and sections, with the exception of the *Melothria pendula* (IV: 68.66, RD: 21.04%, RF: 47.62%), only surveyed within this depth. The dominant species of this section was the *Momordica charantia* with a 97.39 IV, and relative density of 21.20 % and relative frequency of 76.19%.

Table 10. Summary of vegetation analysis of the Green Roof # 3 at 15.24cm depth.

Species Code	Species Name	Relative Density (%)	Relative Frequency (%)	Importance Value
UNK THU	*Unknown Thunbergia spp*	26.82	95.24	122.06
MOM CHA	*Momordica charantia*	23.03	95.24	118.27
CYP KYL	*Cyperaceae kyllinga*	14.76	76.19	90.95
BID ALB	*Bidens alba*	13.86	57.14	71.00
PAS GRA	*Paspalum paniculatum*	6.98	42.86	49.84
OXA ART	*Oxalis articulata*	10.77	33.33	44.10
ASC CUR	*Asclepias curassavica*	3.09	28.57	31.66
EUP GRA	*Euphorbia graminea*	0.70	14.29	14.98

Table 11. Summary of vegetation analysis of the Green Roof # 3 at 20.32cm depth.

Species Code	Species Name	Relative Density (%)	Relative Frequency (%)	Importance Value
UNK IPO	*Unknown Ipomea spp*	50.83	100.00	150.83
UNK THU	*Unknown Thunbergia spp*	25.90	100.00	125.90
MOM CHA	*Momordica charantia*	12.44	90.48	102.92
BID ALB	*Bidens alba*	6.54	61.90	68.45
PAS GRA	*Paspalum paniculatum*	2.25	42.86	45.11
CYP KYL	*Cyperaceae kyllinga*	0.80	28.57	29.38
EUP GRA	*Euphorbia graminea*	0.70	28.57	29.27
OXA ART	*Oxalis articulata*	0.43	19.05	19.48
CIS VER	*Cissus verticilata*	0.05	4.76	4.82
PAS FOE	*Passiflora foetida*	0.05	4.76	4.82

Table 12. Summary of vegetation analysis of the Green Roof # 3 at 25.4cm depth.

Species Code	Species Name	Relative Density (%)	Relative Frequency (%)	Importance Value
MOM CHA	*Momordica charantia*	21.20	76.19	97.39
UNK THU	*Unknown Thunbergia spp*	14.24	66.67	80.91
EUP GRA	*Euphorbia graminea*	15.03	57.14	72.17
MEL PEN	*Melothria pendula*	21.04	47.62	68.66
BID ALB	*Bidens alba*	20.25	28.57	48.82
UNK IPO	*Unknown Ipomea spp*	7.44	23.81	31.25
OXA ART	*Oxalis articulata*	0.47	9.52	10.00
ASC CUR	*Asclepias curacsavica*	0.16	4.76	4.92
PAS FOE	*Passiflora foetida*	0.16	4.76	4.92

The fourth sampled GR (Table 13), as explained in the Methods section this roof not only is located at the UPR-RP but it has different features; this influenced its vegetation composition. This roof contained some of the common species of previous green roofs, i.e., *Cyperacea kyllinga* (IV: 29.26, RD: 3.71%, RF: 25.56%), *Bidens alba*

(IV: 19.11, RD: 3.55%, RF: 15.56%), and *Emilia sonchifolia* (IV: 3.49, RD: 0.15%, RF: 3.33%). It also contained some new species such as *Cymbopogon ambiguus* (IV: 104.49, RD: 27.82%, RF: 76.67%) which was the most dominant, *Kalanchoes x hoightonii* (IV: 99.71, RD: 44.15%, RF: 55.56%) second most abundant and one of the originally planted species.

Table 13. Summary of vegetation analysis of the Green Roof # 4.

Species Code	Species Name	Relative Density (%)	Relative Frequency (%)	Importance Value
CYM AMB	*Cymbopogon ambiguus*	27.82	76.67	104.49
KAL X HOU	*Kalanchoes x houghtonii*	44.15	55.56	99.71
UNK 4-1	*Unknown species # 1*	7.26	38.89	46.15
CYP KYL	*Cyperacea kyllinga*	3.71	25.56	29.26
BID ALB	*Bidens alba*	3.55	15.56	19.11
KAL PIN	*Kalanche pinnata*	11.33	5.56	16.89
SPI ANT	*Spigelia anthelmia*	1.49	14.44	15.94
UNK 4-2	*Unknown species # 2*	0.41	3.33	3.75
EMI SON	*Emilia sonchifolia*	0.15	3.33	3.49
UNK DIO	*Unknown Diodia spp*	0.1	2.22	2.33

Discussion

From our results we can see that vegetation included in the original design was mostly absent by the time we surveyed the sites. It appears that many of the originally planted species were not necessarily suitable for the tropical roof top environment, and, therefore, did not persist. Species like *Tulbaghia violacea*, *Asclepias curassavica* (a native planted later), and *Arachis hypogaea*, were the only species that seemed to be well adapted and persisted in the green roofs with high relative densities and/or frequencies. Most of the other species were not found at all, but some isolated individuals were found for species like *Passiflora foetida, Talinum paniculatum* and *Sedum stahlii.* We found scattered individuals of *Portulaca grandiflora*, *Portulaca oleracea* and *Portulaca pilosa* on some roofs. These are non-native succulent species, recommended for green roof design in tropical wet and dry conditions as stated by Vijayaraghavan (2016), so we suspect they may have been part of the originally planted ones. On the other hand native species were well adapted and spread all over the green roofs almost regardless of the depth. The species that did outstandingly well were *Bidens alba*, *Nephrolepis multiflora*, and *Momordica charantia*; which were found at the highest importance values in more than one roof depth.

From these preliminary results we can propose a list of species that showed good adaptation to the local conditions, such as *Bidens alba*, *Tulbaghia violacea, Nephrolepis multiflora, Arachis hypogaea, Momordica charantia, Asclepias curassavica, Alopecurus pratensis, Paspalum paniculatum, Euphorbia graminea, Cymbopogon ambiguus,* and *Kalanchoes x houghtonii*. These are a mix of both native and non-native species that withstand not only the physical conditions but the competition of other species and the probable presence of local pests. All of them showed high or moderate relative densities and/or frequencies, which can be interpreted as good adaptation to the environment on the tropical green roofs or high resilience of the species to the conditions in these habitats. This species might provide a suitable mix of species to be included in future green roof plantings in Puerto Rico.

As noted in the literature review (Chapter 1), few considerations have been given to which species would be suitable for green roofs in the wet tropics. The region that has the best experience is Singapore and they have not only implement good policies towards the implementation of green roofs but are pioneers in the tropical zone in the establishment of locally adapted species into their designs (Peng Lihua 2012). Singapore has numerous studies that point out that the benefits of this human-made ecosystems can be achieved in the tropics as well as in temperate zones, with the considerations of certain criteria, e.g., precipitation patterns. Even when precipitation and humidity are high in many tropical sites, water availability for plants could be limiting in some green roofs due to relatively shallow substrates and poorly design retention layers. Tan Yok and Sia (2008) highlight some features that could be contemplated for plant selection; one of them is their photosynthesis mode. They suggest plants with Crassulacean Acid Metabolism (CAM) photosynthesis, because they are efficient in water use which is a great feature for dry areas or shallow green roofs. The National Parks Board of Singapore has been performing studies to delimit the plant list for green roof incorporation. Some of the species listed are *Alternanthera ficoidea*, *Bryophylhim fedtschenko*, *Carissa macrocarpa*, *Desmodium triflorum*, *Echeveria spp*., *Habranthus gracilifolius*, *Lobelia ehinensis*, *Plectranthus verticillatus*, *Wollastonia biflora*, among some others (Tan Yok and Sia 2008). These species might also be considered for green roofs in Puerto Rico in addition to the ones identified in this study.

Vegetation performance depends strongly on the conditions of the environment and the resource availability (Raimondo et al. 2015), especially since green roofs are engineered ecosystems that try to emulate ground level ones throughout the incorporation of artificial layers that need to be carefully balanced in order to retain the desire moisture and nutrients for the plants they hold. Green roofs are considered hostile environments for numerous species and the list of those that could adapt and survive high temperatures, dry conditions, and space limitations is scarce (Williams, Lundholm, and Scott Macivor 2014; Oberndorfer et al. 2007). Moreover the substrate depth seems to be one of the key features that determines plant diversity and performance among green roofs as well as humidity retention. Extensive green roofs have an even smaller pool of options as potential plants for their design than intensive ones and, since the maintenance is often minimum, retaining the desired conditions is delegated to the moisture retention layer and substrate composition. If maintenance is regular the number of species could increment and the environment can be artificially managed to comprise a different than natural plant composition. An option proposed to accomplish high survival rates and good propagation is the design from a functional diversity perspective (Van Mechelen et al. 2015), this approach consists in allocating ecological traits among the green roofs in order to achieve the ecosystem resilience rather that aiming for a big list of species that would not survive on long-term and are not necessarily interconnected, these are the so called trade-offs of the ecosystem that could be involve in the design and species selection.

Conclusions

In this study, I found that more tropical studies need to be performed, the list of available species for green roof design needs to be evaluated from local condition adaptability and not from temperate climate previously selected lists, and that the purpose of the green roof needs to be well established in order to design aiming for better outcomes. The surveyed sites need to be revisited to be able to establish if the results obtained in this study were from random conditions or if there is an actual trend towards local vegetation to take over species with low adaptability. Also a decision from the owners of green roofs needs to be taken in order to establish management and maintenance treatments in order to maintain current conditions, to reverse to previous ones or to guide vegetation colonization towards a new composition and function from the green roofs.

In the future there are various things that can be done to enrich the green roof topic in Puerto Rico. An inventory of private and public green roofs could be performed throughout the use of remote sensing tools, an analysis of the public policy in the country towards sustainability measurements such as the green roof implantation to assess the implementation tools and strategies. Also for the sites used in this study, along with the vegetation surveys, water and energy analysis could be incorporated as well.

Acknowledgements

I would like to thank my advisor Jess Zimmerman for his guidance in the vegetation analysis. I would like to recognize greatly the effort of my colleague Rosa Saez, who helped me through the data collection process.

References

Berardi, Umberto, AmirHosein GhaffarianHoseini, and Ali GhaffarianHoseini. 2014. “State-of-the-Art Analysis of the Environmental Benefits of Green Roofs.” *Applied Energy* 115 (February): 411–28. doi:10.1016/j.apenergy.2013.10.047.

Comarazamy, Daniel E., Jorge E. González, and Jeffrey C. Luvall. 2015. “Quantification and Mitigation of Long-Term Impacts of Urbanization and Climate Change in the Tropical Coastal City of San Juan, Puerto Rico.” *International Journal of Low-Carbon Technologies* 10 (1): 87–97. doi:10.1093/ijlct/ctt059.

Dvorak, Bruce, and Astrid Volder. 2010. “Green Roof Vegetation for North American Ecoregions: A Literature Review.” *Landscape and Urban Planning* 96 (4): 197–213. http://www.sciencedirect.com/science/article/pii/S0169204610000782.

Jean, Aur´elien, Teddy Libelle, Fr´ed´eric Miranville, and Maario Medina. 2014. “Vegetalized Complex Partition (VCP): Impact of a Green Roof under a Humid Tropical Climate , Comparison between Hong Kong and Reunion Island.” *Applied Mechanics and Materials* 705: 273–77. doi:10.4028/www.scientific.net/AMM.705.273.

Kamarulzaman, Noorazlina, Siti Zubaidah Hashim, Hasnan Hashim, and Alia Abdullah Saleh. 2014. “Green Roof Concepts as a Passive Cooling Approach in Tropical Climate- An Overview.” In *E3S Web of Conferences*, 3:7. doi:http://dx.doi.org/10.1051/e3sconf/20140301028.

Li, Yanling, and Roger W. Babcock. 2014. “Green Roofs against Pollution and Climate

Change. A Review." *Agronomy for Sustainable Development* 34 (4): 695–705. doi:10.1007/s13593-014-0230-9.

Lugo, Ariel E, and Jeannette Rullán. 2015. "The Conservation Message of the Rehabilitated Facilities of the International Institute of Tropical Forestry," no. November.

Mueller-Dombois, Dieter, and Heinz & Ellenberg. 1974. "Measuring Species Quantities." In *Aims and Methods of Vegetation Ecology*, 84–90. New York: John Wiley & Sons, Inc.

Muscarella, Robert, María Uriarte, David L. Erickson, Nathan G. Swenson, W. John Kress, and Jess K. Zimmerman. 2016. "Variation of Tropical Forest Assembly Processes across Regional Environmental Gradients." *Perspectives in Plant Ecology, Evolution and Systematics* 23 (December): 52–62. doi:10.1016/j.ppees.2016.09.007.

Oberndorfer, Erica, Jeremy Lundholm, Brad Bass, Reid R. Coffman, Hitesh Doshi, Nigel Dunnett, Stuart Gaffin, Manfred Köhler, Karen K. Y. Liu, and Bradley Rowe. 2007. "Green Roofs as Urban Ecosystems: Ecological Structures, Functions, and Services." *BioScience* 57 (10): 823. doi:10.1641/B571005.

Parnell, Susan. 2016. "Defining a Global Urban Development Agenda." *World Development* 78 (February): 529–40. http://www.sciencedirect.com/science/article/pii/S0305750X15002508.

Peng Lihua, Lilliana. 2012. "Green-Roof Thermal Effects in the Context of Climate Change and." University of Hong Kong.

http://hub.hku.hk/bitstream/10722/181517/1/FullText.pdf?accept=1.

Raimondo, F., P. Trifilo, M. a. Lo Gullo, S. Andri, T. Savi, and A. Nardini. 2015. “Plant Performance on Mediterranean Green Roofs: Interaction of Species-Specific Hydraulic Strategies and Substrate Water Relations.” *AoB PLANTS* 7 (0): plv007-plv007. doi:10.1093/aobpla/plv007.

Razzaghmanesh, Mostafa, Simon Beecham, and Telma Salemi. 2016. “The Role of Green Roofs in Mitigating Urban Heat Island Effects in the Metropolitan Area of Adelaide, South Australia.” *Urban Forestry & Urban Greening* 15: 89–102. doi:10.1016/j.ufug.2015.11.013.

Rudel, Thomas K, Marla Perez-Lugo, and Heather Zichal. 2000. “When Fields Revert to Forest: Development and Spontaneous Reforestation in Post-War Puerto Rico.” *The Professional Geographer* 52 (3): 386–97. doi:10.1111/0033-0124.00233.

Saadatian, Omidreza, K. Sopian, E. Salleh, C.H. Lim, Safa Riffat, Elham Saadatian, Arash Toudeshki, and M.Y. Sulaiman. 2013. “A Review of Energy Aspects of Green Roofs.” *Renewable and Sustainable Energy Reviews* 23 (July): 155–68. http://www.sciencedirect.com/science/article/pii/S136403211300124X.

Santana, Kevin Feliz. 2016. “ESTUDIO DE FACTIBILIDAD DE LA IMPLANTACIÓN DE TECHOS VERDES EN UN CLIMA TROPICAL COMO EL DE LA REPÚBLICA DOMINICANA.” Universitat Politécnica de Catalunya. http://upcommons.upc.edu/bitstream/handle/2117/84099/Mem%25C3%25B2ria_FelizKevin.pdf.

Srivastava, Rohini. 2011. “Green Roof Design and Practices :” Kent State University.

https://etd.ohiolink.edu/ap:10:0::NO:10:P10_ACCESSION_NUM:kent1311004642.

Tan Yok, Puay, and Angelia Sia. 2008. *A Selection of Plants for Green Roofs in Singapore*. doi:10.1007/s11252-008-0069-4.

Van Mechelen, Carmen, Koenraad Van Meerbeek, Thierry Dutoit, and Martin Hermy. 2015. "Functional Diversity as a Framework for Novel Ecosystem Design: The Example of Extensive Green Roofs." *Landscape and Urban Planning* 136 (April): 165–73. doi:10.1016/j.landurbplan.2014.11.022.

Vijayaraghavan, K. 2016. "Green Roofs: A Critical Review on the Role of Components, Benefits, Limitations and Trends." *Renewable and Sustainable Energy Reviews* 57 (May): 740–52. doi:10.1016/j.rser.2015.12.119.

Williams, Nicholas S G, Jeremy Lundholm, and J. Scott Macivor. 2014. "Do Green Roofs Help Urban Biodiversity Conservation?" *Journal of Applied Ecology* 51 (6): 1643–49. doi:10.1111/1365-2664.12333.

GENERAL CONCLUSIONS

We can conclude from the literature review that the purpose of green roofs needs to be well established in order to accomplish the desired benefits. Maintenance has to take place in order to ensure the continuation of initial setups in extensive green roofs that lack high moisture and nutrient retention. Also if approached from a national sustainability agenda, green roofs need to be implemented with careful attention to allocation within the city, good resources management, and the support of incentives that can grant or broaden the implementation efforts. Puerto Rico, as well as the rest of the tropics, needs to continue exploring the suitable elements such as plant species, soil mixtures, materials components, and design layouts to ensure the durability of green roofs as novel ecosystems in the tropical zone.

Regarding the vegetation component, we found that plant species incorporated in the original design of green roofs are not necessarily well adapted to the environmental conditions of green roofs. Native species seem to colonize the areas and withstand the local conditions. Species lists provided by other countries with similar climatic and topographical conditions should be explored and combined with local lists to achieve positive outcomes through resilience and survival enhancement of species in green roofs. There are countries such as Singapore that have taken the first steps towards this direction and their procedures could be adapted and replicated in Puerto Rico to evaluate plant persistence, suitability, adaptability, use and application in green roofs in the country.