The Green Roof Landscape of Austin, Texas

A Contemporary Inventory of Green Roof Systems

By

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Introduction and Background

Recent estimates indicate that by the year 2030 more than 60 percent of the global population will reside in urban areas (Lin et. al. 2015). In the United States, as of 2010 nearly 81 percent of Americans lived in cities, while the top 48 urbanized areas accounted for more than half of the entire urban population (U.S. Census 2010). This overwhelming concentration of people within the built environment has resulted in an expeditious urbanization process in which natural ecosystems are replaced by urban sprawl while urban residents are increasingly separated from conventional spaces of nature and the intrinsic value these spaces stand to provide. Additionally, this shift requires fresh perspectives and changing ideals of environmental conservation and how this can or should be achieved in a progressively urbanized context.

To address this widening divide between urban residents and the natural environment, a variety of green infrastructure approaches have gained considerable popularity as a mechanism to provide urban dwellers with access to natural landscapes. Green infrastructure refers to a planned network of natural and semi-natural areas that can offer diverse ecosystem services, protect biodiversity and produce livable urban environments with a critical aspect of multifunctionality, the ability of green space to perform multiple ecological, social and economic functions (Mesimaki et. al. 2016). The consequences of high-density development have limited the availability of green spaces, necessitating a search for new alternative capacities in which to create "nearby nature" (Fernandez-Canero et. al. 2013). Green roof systems have become a beneficial way to address these concerns and introduce verdant landscapes into dense urban areas. These engineered ecosystems have emerged as an exemplary component of green infrastructure strategies due to the long-term economic, social and environmental benefits they can provide to urban communities.

This study takes place in Austin, Texas, a vibrant municipality in the midst of unprecedented and exponential growth. As of July 2016, the population of Austin within the city limits had risen to 947,890, a 17 percent increase since 2010 (U.S Census 2018). The decade ending in 2015 saw a 37.7 percent increase in population for the city of Austin, compared to a 20 percent increase for the state of Texas and an eight percent increase for the United States (Austin Chamber 2016). The city's greater metropolitan population surpassed two million in 2015 and is forecasted to exceed 3 million by the year 2030 (Austin Chamber 2016). These statistics collectively designate Austin as one of the fastest growing cites in the country over the last 20 years.

The city of Austin is also well known for its progressively liberal attitude and environmentally-conscious atmosphere. Approximately 33 million trees provide almost 31 percent canopy cover, designating Austin as one of the most forested cities in the country (USDA Forest Service 2018). In 2014, an economic analysis determined that the city's urban forest provided $34 million in services and benefits to the community in air pollution removal, carbon sequestration and energy savings (USDA Forest Service 2018). The expansion of green roof infrastructure stands to offer similar advantages. In 2009, the Austin City Council created the Green Roof Advisory Group (GRAG) to explore the feasibility of offering energy and stormwater credits as well as other financial incentives to encourage the construction of green roofs and eco-friendly buildings within the city (GRAG Report 2011). This report established a six-phase time line that defines the advancement of green roof policy development, from Phase 1: Introduction and Awareness to Phase 6: Continuous Improvement (GRAG Report 2011). As of the last published GRAG Report of 2011, Austin retains a Phase 3 designation, an intermediary stage of Action Plan Development and Implementation.

This combination of characteristics, increased population and development as well as a vested interest in the outdoor environment and green and sustainable solutions make Austin a compelling city in which to study the benefits and implications of green roofs and green infrastructure opportunities. Several organizations including the GRAG and the City of Austin Watershed Protection Department have ventured to create a green roof inventory available to the public through annual reports or city websites. However, these attempts have provided an inadequate and incomplete visual representation of Austin's green roof landscape. There is no current or comprehensive database, spatial or otherwise, tracking the existence or development of green roof structures. The primary objective of this project was to create a green roof geographic information system (GIS) for the city of Austin, Texas. This research highlights effective strategies of green roof design for central Texas, how these spaces contribute to the complex mosaic of urban life and how these settings relate to current discourses surrounding ecological conservation.

The development of a green roof spatial database seeks to establish the prevalence, distribution and composition of residential, commercial and institutional green roofs in Austin, Texas. Additionally, several complementary questions were investigated to provide individual details of each green roof design and to further support the findings of this inventory. What creates and defines an efficiently functioning green roof system: successful plant ecology, effective management and maintenance, or the human utilization and enjoyment these spaces can provide? What are the prevailing management strategies and ecological characteristics of green roofs within the city? What are the perceptions, attitudes and managerial motives or desired environmental outcomes of green roof supervisors, designers and owners? And finally, can green roofs and corresponding hybrid landscapes offer expanded ecosystem services to urban residents while alleviating certain pressures of urban development?

Additionally, this research addressed several probable insights concerning these primary questions. First, the relative success or failure of a green roof project must rely on adaptive collaborative management practices and interorganizational support from diverse stakeholders at varying levels of agency. Second, the majority of green roof systems within the city feature predominantly native plant species, with adaptive or non-native plant assemblages more commonly found on intensive or semi-intensive green roofs present on residential apartments or other buildings designed for outdoor recreational use. Third, the environmental benefits of green roofs such as stormwater mitigation, ecological performance and efficiency as well as energy use reduction are the most sought after and desirable impacts in the minds of green roof designers. However, where green roofs are constructed with a social function or use in mind, the economic potential of these projects may outweigh the environmental benefit available. Furthermore, green roofs and the diversity of hybrid landscapes stand to offer a wealth of ecosystem services to urbanites, including recreation, recuperation from stress and educational possibilities. Finally, there is an unequal spatial distribution of green roofs in the city, an issue that requires further attention for green roofs to not solely represent an exclusive or affluent market endeavor. This area of research surrounding green infrastructure development necessitates a complete understanding of Austin's green roof landscape in order to promote further green infrastructure policy as well as support future research in the fields of urban sustainability and ecological conservation.

Basics of Green Roof Design

Over the last decade, green roof development has seen a drastic increase throughout the country with over a 28 percent increase in green roof construction during 2010 alone (Jungels et. al. 2013). Rooftops can typically account for up to 32 percent of the built area of a city, representing a valuable opportunity for the implementation of green and sustainable architecture (Henry and Frascaria-Lacoste 2011). Construction of green roof systems consists of two general types: intensive and extensive. Intensive roofs have a deep soil substrate, large amounts of biomass able to accommodate sizeable trees and shrubs, are green and aesthetic, provide accessible green space for urban residents and office workers, and require regular maintenance (Lorimer 2008). These green roofs are the type most prevalent in the imagination of the broader public and are designed to resemble public parks or gardens, conforming to more traditional ideals of what *nature* entails. Intensive green roofs generally feature a soil depth of 6 inches - 4 feet, provide for greater diversity of plant species, range of design and better insulation properties for stormwater management and energy use reduction (GRHC 2006).

Conversely, extensive roofs have a much thinner soil layer and require minimal management. Although the smaller biomass of extensive roof systems supports a narrower range of possible plant choices, mostly sedum, grass or wildflower-based plant communities, this type of "brown roof" could have the greatest potential for urban conservation and the enhancement of biodiversity (Lorimer 2008). Extensive green roofs are lightweight, usually feature less than 6 inches of soil, are suitable for large areas and require only low maintenance costs to reach establishment (GRHC 2006). These attributes characterize extensive green roofs as a valuable potential tool to cover the largest area of the rooftop city-scape at cost-effective measures in order to take greatest advantage of the diverse environmental benefits of green roof systems. This lower price point, both in installation and maintenance costs, make these green roofs a more realistic and attainable option for a wider range of society.

Some green roofs have media depths and materials that vary throughout the structure, creating distinct pockets of soil composition that enable many different types of plant varieties and design opportunities, including rock, wood or debris piles that create ecological heterogeneity, specialty niches and wildlife habitat. These semi-intensive roofs are less common but are of particular interest as they are also cost effective, widely replicable and offer diverse planting options (Jungels et. al. 2013). These green roofs provide the best features of both intensive and extensive green roof systems and perhaps are the most promising example of ecological biodiverse habitat within the built environment (GRHC 2006).

Many green roofs are built onto pre-existing roofs through a process of structural adjustment and prefabrication, while many new buildings incorporate them into their design from the initial planning stages. Green roofs typically consist of: 1) a waterproof and root resistant membrane to prevent roof damage and leakage; 2) a drainage layer, which may act as a water reservoir for plant use; 3) a filter membrane that prevents fine sediments from percolating downwards; 4) a sediment layer of chosen soil medium, varying in depth and inorganic materials, approximately 4 inches to 3 feet deep; and 5) a surface vegetation layer that can be seeded, planted, turfed, left to colonize naturally or any combination of these options (Francis and Lorimer 2011). Finally, green roofs can either be modular or monolithic. Modular systems are composed of prefabricated and pre-planted square boxes of soil that are fit into place like Tetris pieces above the waterproof membrane. This technology allows for individual pieces to be easily removed and replaced as certain sections fail or lose their seasonal interest. However, these "component systems" have been found in some cases to not function efficiently in the inconsistent climate of Texas that features prolonged periods of drought and oppressive heat followed by flash floods and seasonal storm events. Monolithic roof systems are far more common and successful, featuring a deeper and interconnected soil substrate that allows for deeper root systems, broader species diversity, and greater moisture retention and root insulation (GRAG Report 2011).

Social and Environmental Benefits of Green Roof Systems

Green roof systems possess the capability to extend numerous public and private benefits to urban communities. Green roofs are well documented to mitigate the urban heat island effect (UHIE), ameliorate stormwater runoff, reduce energy requirements of buildings, enhance air quality and increase biodiversity and corresponding habitat (Fernandez-Canero et. al. 2013). The UHIE is the temperature increase in urban centers caused by the replacement of natural vegetation with pavement, buildings and other structures necessary to accommodate growing populations (Wong 2002). These impermeable surfaces convert sunlight to heat, while the disappearance of natural vegetation and the construction of tall buildings prohibit the occurrence of natural cooling processes such as evapotranspiration and wind (GRHC 2006). A Canadian study found that 25 percent green roof coverage can reduce the UHIE by up to 1.8 F degree over roughly a fourth of a medium-large sized city, while with 50 percent of green roof coverage cooling was increased to 3.6 F degrees (GRHC 2006). The proliferation of green roofs within dense urban environments would certainly help to alleviate this troubling aspect of environmental health and degradation in the urban city.

In May of 2015, Austin experienced one of the worst flood events on record. The Memorial Day weekend floods of 2015 dropped more than 10 inches of rain in a single hour over parts of central Texas, caused several area rivers to crest well above their historical rising points and killed 14 people while damaging or destroying over 2100 homes in neighboring Hays county alone (Austin American Statesman 2015). Green roofs, primarily the extensive variety of deeper soil substrates, can reduce total run-off by 60 percent and detain 85 percent of the first flush in a rainfall event for several hours before its release into a sewage system (Hathaway 2004). By delaying stormwater runoff, green roofs effectively reduce instances of flooding, help prevent untreated sewage from entering local watersheds and reduce the pressure on existing infrastructure (GRHC 2006). In an era when dangerous flooding events seem to occur with increasing frequency, coupled with the added vulnerability of more people living within the urban core, green roof systems provide a useful advantage to address this potential environmental hazard.

Similar to the positive effects green roofs and associated soil cover have concerning stormwater management, increased thermal mass also enhances thermal insulation, thus reducing structural heating and cooling costs. The presence of vegetation enhances surface reflectivity as well as evapotranspiration, the process by which water is transferred from land to the atmosphere by evaporation from soil and the respiratory process of plants. Evapotranspiration effectively lowers a roof's ambient temperature while reflectivity expresses a ratio of radiation absorbed to the total amount of incoming radiation (GRHC 2006). Traditional roofs have a reflectivity rate of 58 percent, while green roofs have one of 12 percent, demonstrating the heat absorbent capacity of green roof systems (Sonne 2006).

Other critical issues of importance related to the negative health effects of life in the urban city are poor air quality and increasing levels of air pollution. Green roofs mitigate air pollution levels by lowering extreme summer temperatures, trapping particulates and capturing harmful greenhouse gases and air pollutants such as nitrogen dioxide, nitrogen oxide, sulfur monoxide and carbon monoxide (GRHC 2006). At present, urban air quality has been estimated to cause the deaths of 800,000 people per year globally (Kenworthy 2002).

These collective qualities are especially relevant in the context of combatting the devastating consequences of global climate change. In October of 2018, the Intergovernmental Panel on Climate Change (IPCC) issued a stark warning that humanity may have as little as 12 years to avoid total climate change catastrophe, to limit the increase of global temperatures and therefore the elevated risks of drought, floods, extreme heat and poverty for hundreds of millions of people (Intergovernmental Panel on Climate Change 2018). The aforementioned characteristics of green roofs constitute a variety of constructed ecosystems providing different technical and ecological benefits that are expected to reduce these possible consequences of climate change (Mesimaki et. al. 2017). The further resilience and adaptability of urban areas to future economic, housing and environmental demands can be enhanced through the appropriate design and management of urban green spaces (Niemela 2014). The continued implementation of green roofs and green infrastructure projects can establish a forward-looking and future-oriented approach as well as conservation responses for changing biophysical conditions and issues of socio-ecological adaptation in the face of unprecedented change (Lennon 2016).

Green roofs also offer substantial benefits to urban biodiversity in their capacity to create habitat and specialized niches for colonizing species, the presence of a wide range of different functional typologies in the urban seed rain and high potential for spontaneous biodiversity as well as increased temporal plant assemblages (Lorimer 2008). It has also been shown that these urban ecosystems can provide increased foraging habitat, the availability of successful breeding sites and valuable nectar sources for diverse pollinator species (Francis and Lorimer 2011). These spaces can also act as “stepping stones” for migrating species, a green corridor to facilitate wildlife movement (GRHC 2006). Furthermore, engineering a roof to support a specific threatened or declining suite of species can be achieved (Francis and Lorimer 2011). This may necessitate the use of a specific soil medium or depth as well as carefully created habitat niches but could potentially be utilized to bolster the preservation or resurgence of several central Texas endangered species, including Black-caped Vireo or the Western Burrowing Owl. Finally, green roofs that have been designed for biodiversity goals generally are extensive and require less maintenance and less financial input than green roofs designed for cosmetic or ornamental purposes, making them a more viable option for broader scale, and more broadly inclusive, implementation and installation.

A final important element of environmental benefit concerning green roof systems is their ability to divert millions of tons of waste from landfills. Green roofs prolong the life of waterproofing membranes significantly because they provide protection from harmful moisture, heat, ultraviolet radiation, maintenance traffic and freeze-thaw cycles (GRHC 2006). Correspondingly, green roofs also contribute to landfill diversion through the use of recycled materials in growing mediums and by prolonging the service life of heating, ventilation and air conditioning systems through decreased use (GRHC 2006).

From a social standpoint, green roofs can offer a multitude of ecosystem services to urban communities. Green roofs contribute to the livability of urban areas in numerous ways by providing green space for everyday renewal and relaxation, recreation, strengthening social cohesion and interaction, softening the hard cityscape and increasing urbanite’s contact and association with nature (Mesimaki et. al. 2016). Other associated provisions include opportunities for recuperation from stress, educational possibilities, noise abatement and production of local food (Niemela 2014). Green roofs also promote the creation of outdoor amenity space and in turn the production of local job opportunities and local livelihoods. Additional ecosystem services relate to numerous environmental categories previously mentioned, that either support biodiversity (nutrient cycling, soil filtration, photosynthesis, pollination), aspects of land management (the regulation of climate, water, erosion, hazard and disease), and the supply of material and cultural services (production of food, fiber and fuel as well as aesthetic value) (Evers et. al. 2018). It has also been theorized that the presence of a green roof can raise the property value of single-family homes due to their aesthetic beauty and energy insulation. However, there is very little if any research supporting this claim.

Finally, green roofs can produce an excellent lens through which to explore the complex human relationship to nature in cities as well as how this interaction takes place, challenging the dualistic concept of the nature/city divide (Loder 2014). Green roofs have demonstrated the ability to evoke sensory memory of past nature experiences and to create a sense of hope about a desired re-balancing of the natural and human-made world (Loder 2014). This sense of hope and restoration is linked to larger debates around the quality of life and public space in cities and of a collective well-being and sense of place (Loder 2014).

Research Methods

To briefly restate the primary objective of this research, this project sought to produce a current and comprehensive inventory of green roof systems within the city of Austin, Texas. Additional research questions to support and complement the findings of this inventory were: What creates and defines an efficiently functioning green roof: successful plant ecology, effective management and maintenance, or the human utilization and enjoyment these spaces can provide? What are the social and environmental benefits of green roof systems and how are these values represented within the green roof landscape? And finally, can green roofs and corresponding hybrid landscapes offer expanded ecosystem services to urban residents while alleviating certain pressures of urban development and human and environmental stressors of life in the urban city? This research entails both data collection and data analysis for each essential aspect of this project: mapping data used to create the green roof database as well as data acquired from interviews and on-site fieldwork to examine values, uses and impacts of green roofs throughout the city.

Green Roof Inventory: Data Collection

Data collection for the development of a green roof database began with the selection of valuable informants that could assist in the process of locating every existing and proposed green roof project in the city of Austin. This category of research participants was chosen primarily from landscape architects, city departmental agencies and green roof contractors as these particular organizations and individuals are most directly involved in the design, execution and construction of green roofs and green infrastructure projects. These subjects were found through available online resources as well as compiled from existing professional contacts of the author acquired over 15 years of employment in the horticultural industry. Initial contact was established through email communication and a request to participate in ongoing graduate research concerning urban ecology, green roof and green infrastructure development. Subsequently, short phone interviews lasting less than one hour were conducted with each participant and were predominantly focused on the location of green roof sites in order to provide an accurate and up-to-date geographical representation of Austin's green roof landscape. Additionally, series of questions were asked to identify each green roof type (extensive, intensive, semi-intensive), the year it was constructed, engineering specifics, soil composition, soil depth and individual plant profile.

The primary goal of these preliminary contacts was to schedule an on-site meeting to access, observe and analyze each green roof system identified. Numerous on-site visits have been conducted, typically lasting between one and two hours. At each site, either the designer or the manager of the green roof was present to discuss the design process, the various parties involved within the process, the goals of the project and the soil composition and plant assemblage chosen. Various success stories or unfortunate lessons learned were also discussed, providing valuable insight into which particular tactics and green roof design decisions perform best for optimal success in a central Texas climate. However, as a sort of mixed blessing, this research has yielded far more green roof locations than the scope of this project has allowed the timeframe to visit. There is still considerable work to do in order to personally visit each green roof site and to examine each corresponding set of specific details. This aspect of this project will likely continue past the completion of this paper. Each email contact, phone conversation or on-site meeting concluded with a request for additional valuable interview candidates in an effort to engage in "snowball sampling" and to accomplish complete saturation and collaboration with individuals that could aid in the full realization of this research.

Several documents provided the structural foundation for a contemporary green roof database. The Watershed Protection Department for the city of Austin provided several GIS shapefiles that featured the location of 16 different commercial and residential green roof systems. These green roofs are also featured on the department's website, the only green roof database previously available to the public. However, this website also features other sustainable community projects such as rain gardens and school vegetable gardens, thus creating a valuable forum for the display of green infrastructure initiatives, but also significant ambiguity as to the existence of green roofs specifically. GRAG reports from 2010 and 2011 were also useful in the precursory phase of green roof exploration and database development. These reports featured seven green roof systems, many of them overlapping with the Watershed Protection Department's shapefiles, but also producing several additional sites. Supplemental locations and addresses were discovered through the interview process, on-site visits and further examination of online archives.

All research participants were given the option of remaining anonymous in order to preserve intellectual property, integrity and camaraderie. Several respondents also chose to remain anonymous so that their personal professional opinions not be broadly shared and unfairly used to define their overarching professional reputation. All residential green roofs were assigned a nearby street intersection rather than an exact street address to preserve the owner's privacy.

Green Roof Inventory: Data Analysis

Once it was determined that all existing and proposed green roofs within the city had been located, data analysis of the green roof database component of this project began. All green roof locations collected over the course of this research were uploaded into Microsoft Excel to create a simple data table featuring just two columns: a listing off all commercial, institutional and residential buildings that contain a green roof system and their corresponding location denoted by a physical address or nearby intersection. This data table was then uploaded into ArcGIS and geocoded to create a visual representation of Austin's current green roof landscape. This geospatial database was designed to be straightforward and practical, utilizing only several essential layers of information: a landscape image of Travis County as a base map, major roads and highways to provide a sense of orientation and spatial placement, and finally the pinpointed locations of the green roofs themselves. Two distinct GIS maps were eventually created: a "before" variant featuring the sixteen green roof locations previously available to the public via the Watershed Protection Department's website, and an "after" map product, a complete and accurate visual representation of all current green roofs within the city of Austin. These two maps side by side highlight the importance and value of this research and the necessity of an up-to-date depiction of the local green roof industry. Several additional GIS maps were created that showcase individual mapped variables including green roof type, building category and plant composition (*see Appendix*).

Interviews: Data Collection and Analysis

The second phase of data collection for this paper consisted of 25 semi-structured informal interviews to assess personal aesthetic attitudes or perceptions, social and environmental benefits and values, as well as diverse goals and desired impacts of green roof development and installation. In addition to the research participants previously mentioned, collaboration was also sought from green roof property owners and academic experts in the fields of sustainability and ecological conservation. Similarly, initial contact was made through email invitation to participate in this research, followed by a request to schedule an in-person or telephone interview and potentially a future site visit to green roof locations. Interviews lasted 30 minutes to an hour and were modified slightly to address the specific knowledge, skills or expertise of each individual participant. Again, interviews concluded with a request for additional colleagues or industry professionals that would be of certain value in the successful completion of this research.

Qualitative interview prompts of roughly 10 questions were issued to all participants. These questions were designed to examine the diverse opinions surrounding the social and environmental benefits of green roof systems and to discuss the intended goals and contemporary mission of ecological conservation in an increasingly urban and industrialized context. In regards to my first research question, what defines a successful or an efficiently functioning green roof, the conversation was geared towards the discovery and determination of certain design tactics that both create a thriving and productive landscaped ecosystem while also meeting the intended goals of each specific project. What combinations of plant species, soil substrate depth and soil medium composition tend to produce not only living but thriving ecological communities that persist in the long-term? How does this affect the availability of habitat to biodiverse organisms? What maintenance and management strategies are leveraged to ensure a successful green roof system and are these strategies written into the design process or project charter from the initial stages of development? How is cooperation and coalescence between diverse stakeholders achieved to create common goals and understandings? Furthermore, what are the intended goals of a green roof project and how are these particular desires met? Are certain green roofs meant to provide outdoor recreational space, to provide insulation for the underlying building or to reduce stormwater runoff, and how are these varied intentions manifested through plant profile choice and project design? Finally, were these goals achieved or was another outcome produced that was unanticipated?

Closely related to these ideas of desired goals and wide-ranging uses, my second research question addresses social and environmental benefits of green roof systems. Inquiry was primarily dedicated to which aspects of green roof implementation are considered more critically significant and how these beliefs affect the decision-making process. What drives the architects of most green roof systems to create such spaces, the social or environmental values they can provide? Similarly, what motivates residential green roof owners or commercial clients to install green roof systems? What are the most frequently desired environmental impacts of green roofs: stormwater runoff reduction, carbon sequestration, energy reduction or ecological functionality? Which environmental aspect of green roof systems is considered most essential in our central Texas climate and our distinct urban landscape? How does Austin compare to other cities recognized for green infrastructure development and what factors can stimulate improvement and expansion of public green incentives? And lastly, what percentage of green roofs within the city perform a more social function, and how does this compare to the apparent premier importance of environmental benefits?

Parallel to this last statement, the final category of questions concerned the proliferation of ecosystem services for urban residents associated with green roof development. In an era of exponential growth within the city of Austin that does not appear to subside anytime soon, it is crucial that such development be smart development. This line of inquiry considered the social value of green roof systems and how these benefits can be translated to serve an environmental function as well, reducing the devastating impact of urban sprawl and ecological degradation found in urban environments. What types of values do green roofs represent to urban residents and how are these spaces utilized for outdoor enjoyment? Which green roofs truly exemplify this dual benefit of social and environmental considerations? How does the public react to various types of green roofs and which green roof systems are more preferable over another and for what reasons? Finally, is the expansion of ecosystem services a valuable tool to increase green roof infrastructure and policy?

All interviews were recorded on an audio recording device and participants were given the option of abstaining from the recording process. Detailed hand-written notes were also taken. Documentation of the interview process was later transcribed and coded for several prevailing themes and patterns of importance. Data analysis began with a first pass of *open* or *descriptive* coding through all materials to distinguish between the two fundamental elements of this project; the green roof inventory and subsequent semi-structured interviews (Cope 2010). Then, a second round of more focused descriptive coding was conducted on each research category. Within the green roof inventory, codes such as residential, commercial, institutional or extensive and intensive were used. Additionally, more specific codes concerning the individual components of green roof systems, such as plant profile, soil characteristics and maintenance strategy were identified. With regards to the interview portion of this project, codes focused on two distinct elements, social and environmental benefits of green roofs and sustainable infrastructure. Within these categories more specific distinctions were then coded for, such as outdoor recreation and recuperation from stress, or stormwater attenuation, habitat diversity and ecosystem generation. The majority of coding was primarily *in vivo*, or taken word by word directly from respondent's discourse (Charmaz 2003). Focused coding was also used to identify variations within diverse responses as well as comparisons among various persons, beliefs, experiences and situational accounts of green roof design, construction and enjoyment (Charmaz 2003). This coded analysis was then used as a valuable instrument to efficiently understand the connections amongst large amounts of information and to successfully create the final written analysis.

Results

Green Roof Inventory

The formulation of a contemporary green roof inventory yielded a total of 58 commercial, residential and institutional green roof systems, producing an additional 42 green roof sites than were previously known or promoted publicly through the city of Austin's Watershed Protection Department website (*see Figure 1*). The Green Roof Advisory Group (GRAG) had also published a report in 2011 identifying seven of Austin's most well known and established green roofs as model examples of varying green roof classifications and diverse purposes. The findings of this research produced more than eight times this antiquated amount, once again highlighting the importance and necessity of this study in the development of an up-to-date and complete catalog of Austin's green roof landscape.

The overwhelming majority of green roofs within the city are concentrated in densely developed downtown neighborhoods, situated between the two major highways of Interstate I-35 and Mopac Loop-1, and extending northward from Town Lake to the area surrounding the University of Texas. 27 green roofs lie within this district, 14 of them representing luxury high-rise residential condominiums or student housing apartments. Two additional apartment complexes featuring green roofs systems lie directly outside this downtown designation, totaling 16 apartment buildings associated with green architecture within the downtown environment. This number is highly indicative of green roofs' capacity to provide ecosystem services to urban dwellers, furnishing green space for outdoor recreation, recuperation from stress and a meaningful experience of the natural elements.

An examination of residential green roofs contributed 14 sites to the project database, a number drastically enhanced from previous inventories. In contrast to 17 residential apartment buildings, this number represents single family homes and landscapes designed at the individual owner's specific request (*see Figure 2 and Table 1*). These locations and site attributes were confirmed by various landscape architects responsible for each specific design. However, the owners, and in most cases the green roof "managers", of these properties were unable to be contacted due to confidentiality agreements and a concern for their privacy. Despite this difficulty, several green roof owners were able to become valuable informants, citing their most common reasons for green roof installation as the provision of green and accessible amenity space as well as personal therapy and a connection with outdoor nature. Aesthetic beauty was also a common reason for the construction of a green roof. One homeowner stated, "My home and garden are my own personal piece of heaven. The garden shed used to be an eye-soar, but now with the green roof you can barely tell where the garden ends and the structure begins." It was surprising to hear that personal property values or energy reduction possibilities did not factor into these decisions. Throughout this process, it has become apparent that property values are more heavily dependent on what structures lie adjacent to green roof systems and provide the associated view or vista, rather than the inclusion of a green roof benefitting the associated property itself. Most residential green roofs were maintained by the owners themselves, although some projects, especially those of a larger scale, utilized the assistance of monthly or biannual maintenance crews.

There are numerous outliers present, generally concentrated within northeast and west Austin with several located in the far south side of the city. These nine green roofs are mostly comprised of medical, educational, recreational and commercial office buildings. Another interesting component of the green roof inventory was the inclusion of proposed projects that are still in the final phases of planning or construction. Out of five ongoing green roof projects across the city, two in particular deserve considerable mention. The Texas Capital Complex Master Plan 2018 has been proposed and undertaken by the Texas Facilities Commission and is scheduled to near completion by the spring or summer of 2022. The ambitious project proposes tree-lined pedestrian avenues spanning several city blocks between Martin Luther King Blvd. and 16th street, several expansive below ground parking garages to alleviate downtown parking unpleasantries and numerous new buildings that serve governmental, retail and institutional functions. All below ground parking lots will be under pervious cover and feature green roof elements while all newly constructed buildings will contain green roof systems of varying size and purpose, whether they provide outdoor space for visitors and office workers or extensive green roof templates to minimize rainfall runoff. Secondly, The Domain, a high-density office, retail and residential center in north Austin and a textbook example of the development method known as New Urbanism, has 13 green roofs currently projected for installation over the next two years. This project in particular represents a valuable opportunity to introduce vegetation and diverse "stepping stone" habitat into an otherwise monotone landscape of concrete and steel.

The composition of green roof varieties within the city is dominated by extensive examples, as well as semi-intensive roofs featuring predominantly extensive elements (*see Figure 3*). All residential green roofs encountered in this study are extensive roof systems, with only a few consisting of semi-intensive areas to produce specialized niches and preferable microclimate for the use of certain desirable plant species. Nearly all apartment buildings or residential units containing green roofs are primarily semi-intensive featuring only limited intensive elements, the latter represented solely in minimal areas to allow the use of larger trees and shrubs in order to produce a more layered and lush appearance. These roofs feature predominantly turf grass communities in order to establish the existence of open green space to use for leisure and recreation within the concrete surroundings of downtown Austin. This space usually contains a pool and consists of the outdoor amenity space for the associated dwelling. An excellent case of the semi-intensive type is the Congress Tower office building. This project represents one of the first and only large-scale retrofits of a green roof onto an existing building in the entire country. Hopefully, this massive undertaking and likely future success will inspire additional future investment into the conversion of many more properties lacking in sustainable details.

Only three buildings within the city are truly consummate examples of an entirely intensive green roof. Austin's City Hall boasts the deepest soil substrate found within this study, 3-5 feet, able to satisfy depth requirements for large trees and shrubs, such as live oaks, mountain laurels and Texas redbuds. The Dell Children's Medical Center perfectly epitomizes the possible social benefits of green roof systems, providing a tranquil and restorative area of diverse plantings to foster health and well-being as well as environmental benefit. The Austin Public Library features a mostly intensive green roof pallet ranging to several smaller areas of semi-intensive or extensive plantings. Opened to the public only a year ago in October of 2017, this green roof represents one of the newest and one of the most broadly accessible rooftop gardens in the city, a favorite place for many to meet, enjoy company and the beauty of natural spaces as well as a quiet place to reflect and read. All three of these examples as well as most residential complexes clearly have the financial capacity to invest in not only the building substructure but the substantial biomass of soil necessary to accommodate such projects. These requirements can be extremely cost-prohibitive to the majority of smaller-scale interests, especially a typical residential homeowner looking to invest in green infrastructure.

Characteristics of a Successful and Efficiently Functioning Green Roof System

Across the multitude of organizations, entities, designers, architects, managers and horticulturalists that envision and execute the various options of green roof system development and installation there are many divergent opinions as to which strategies perform best and allow for optimal success in any particular ecoregion. However, this study has clearly illuminated several overarching thematic commonalities and corresponding tactics for use within central Texas.

Any landscape that reaches its culmination in a thriving, productive, seasonally verdant and dense establishment can trace its success to a nutrient-rich and appropriately chosen soil medium. As briefly noted earlier, an important first consideration in the selection of a soil blend is the weight of the soil mass, both unsaturated (dry) and saturated (immediately after a watering cycle or significant rain event). Heavier soil blends will require a greater structural load capacity on the architectural frame of the building's rooftop as well as greater logistical considerations in the conveyance of the chosen material to the rooftop surface. Due to these limitations, a lightweight soil blend is highly preferable. A frequent combination found in many Austin green roofs is roughly 20-30 percent compost, 10-20 percent sand and up to 60 percent expanded shale. Expanded shale is made from naturally sourced clay or slate that's been heated in a rotational kiln until it becomes a lightweight, porous, ceramic aggregate, utilized fir its ability to increase drainage and improve soil aeration (Living Earth 2016). A high quantity of expanded shale provides excellent air pockets for superb root development and allows for ideal water infiltration through the soil, but is low in mineral and nutrient content, thus necessitating a sizeable compost component to provide abundant organic matter. Other blends examined also included a portion of compost but were additionally comprised of decomposed granite, perlite and pumice. Decomposed granite is a mineral naturally high in phosphorous, the primary nutrient involved in healthy root production. Perlite is an amorphous volcanic glass that has high water retention value, while pumice is a type of volcanic rock that retains a porous foam-like structure. Both are incredibly lightweight, aid in the drainage process and have moisture retention qualities, making them ideal for use in green roof systems. Several research participants referenced recycled construction aggregates such as crushed tile, crushed brick or paving stone, materials that have gained considerable attention and popularity due to their ability to be reconstituted into another use and therefore their truly sustainable nature. These materials also assist in drainage, root development and water filtration. A valuable point repeatedly made by numerous informants was the importance of sourcing materials from the nearest possible location. To import less, to utilize local sources whenever possible and to create a closed-loop system of inputs is always the goal. One horticulturalist stated, "To promote a project as sustainable and then to import materials from all corners of the globe just makes no sense. It defeats the whole point." To pursue sustainability projects with an unsustainable mindset that compromises the very mission statement of the initiative is an incredibly undesirable situation for most green roof professionals, one they will avoid unless there is absolutely no other option.

Appropriate soil selection is of paramount importance for any green roof system to function efficiently. An unfortunate example of a poorly chosen soil medium is apparent in the green roof atop the UT Student's Center. Consisting of mostly a clay-based soil substrate, the plant communities present have consistently died leading to an end result of a virtually empty green roof characterized by bare soil and exposed irrigation piping. Clay soils inhibit the drainage essential for most native plant species to thrive, and in severe flooding events is incredibly detrimental, leading to rot, disease and fungal issues.

Additionally, clay soils compact easily, suffocating root systems and placing increased pressure on irrigation and other mechanical systems. For this green roof to become a success, an entire overhaul of the soil substrate through amendment practices or a complete replacement of the soil medium is necessary, both very expensive and labor-intensive feats to accomplish.

Another primary aspect of soil medium assembly is soil depth, the element of separation between intensive and extensive roof systems. For many green roof designers and landscape architects this conversation marks a point of contention and a lack of realistic expectations with potential clients. The shallower the soil medium, the cheaper the overall cost of the project but also a more limited plant pallet. Educating clients about their particular landscape preference, associated desired plant species and exactly what type of investment and soil depth this will require is always a foremost and essential discussion. Furthermore, if building insulation is a principal reason for a green roof installation, the soil component of any project can accomplish this function even without the inclusion of vegetative matter. In this instance, a deeper soil substrate is advisable, although at this level of investment the addition of plants is almost certainly a forgone conclusion.

There are varying opinions on what an ideal soil depth for green roofs of each category is in central Texas, primarily related to the intense and unrelenting heat of our summer season as well as the potential of prolonged drought. These choices are also dependent on the goals of each project, what plant species are chosen and the purpose of the project: functional, ecological, or amenity based. A large subset of informants placed the absolute minimum for extensive green roofs at 6 inches, representing a purely ecological function most closely related to the “brownfield” varieties discussed earlier, generally geared towards habitat creation, biodiversity or the provision of a natural view. However, the majority of participants placed this minimum at 12 inches, widely considered to be sufficient for adequate root insulation and water retention in order to sustain plant life through seasonal difficulties. This depth will easily accommodate sedums and succulents, most native perennials, wildflower meadows, or even specific varieties of native grasses, producing the desirable effect of a “pocket prairie”. It is important to note that many native grasses have incredibly deep root systems, some reaching 8-10 feet in depth! In a natural prairie system this supports the plant in times of drought and helps to aerate and increase tilth of the native soil. However, in a shallow green roof system, these plants may need to be replanted long before they near the end of their lifecycle, every five-ten years or so. Larger shrubs require at least 2 feet of soil depth, while substantial tress require at least 4 feet. In most cases where large trees are present, such as City Hall, they are placed within a trench that runs only through certain parts of the rooftop area. This allows for the inclusion of larger tree varieties but does not demand that the entire roof area feature so deep of a soil, thus requiring the additional structural and monetary investment discussed previously.

Clearly, the most fundamental and intriguing component of any green roof project is the featured plant assemblage, the vegetative landscape instantly associated with these structures. The state of Texas contains 10 distinct ecoregions with Travis County and Austin specifically existing on the dividing line between the western Post Savannah Oak region and the Blackland Prairies to the east (Texas Parks and Wildlife 2016). However, the Environmental Protection Agency (EPA) actually classifies Travis county as containing three ecoregions: Texas Blackland Prairie, the Edwards Plateau and the East Central Texas Plains (Environmental Protection Agency 2012). These are important distinctions to make as plant varieties that perform well in distant areas of the state will not necessarily acclimate to use in Austin. Additionally, the native plant guidelines of the EPA are what most local horticulturalists and green roof designers define as central Texas natives and therefore utilized most frequently in ecological restorations and rooftop garden designs.

This topic also recalls the dialogue of novel ecosystems, the use of adaptive non-native plant species and diverse planting options to satisfy varied functional, aesthetic, ecological and social purposes. The overwhelming instinct for all green roof professionals interviewed was to use natives whenever and wherever possible, but to accept that certain project goals as well as potential seasonal or spatial interests as well as social functions may require the use the non-native cultivars. Most informants confirmed that most green roof plant pallets feature at least 80 percent native options, while non-natives were used on a case by case basis to afford specific values (*see Figure 4*). An example of this is the inclusion of an evergreen screen, non-native evergreen shrubs of a specific drought tolerant and shallow root system variety that could cover unsightly A/C units or other industrial machinery components. Another example of this practice is the use of numerous annual planters to display bursts of seasonal color in the height of winter or summer months when most natives are either dormant or between bloom cycles. However, many designers restricted the use of annuals to self-seeding native wildflowers, annuals by exact definition but also perennialized in that they re-seed their next generation, creating an established stand of seasonal blooms that expands with each passing year. One designer clearly expressed his opinion of this practice, “I do not believe in the use of true annuals, ever. They are not self-sustaining and that is the end goal of every green roof that I install”.

The use of invasives was strictly forbidden as an unspoken rule amongst industry members, and no green roof within the city was found to promote the use of even one invasive intentionally. Several sites, particularly high-rise apartment buildings that perform an entirely amenity-based function still maintained at least a 50 percent native rule of thumb, promoting landscapes that are “native enough” to persist in a central Texas climate but also add year-round aesthetic variety and provide an image of conventional nature to their urban residents. It is of critical importance for most green roof designs, especially those with both an ecological and social goal in mind, to exhibit a “layered landscape,” a fully integrated and representational ecosystem that contains groundcovers, perennials, shrubs, trees and climbing vines.

From a conservation standpoint, one informant stated, “I would guess that only 5-10 percent of natives within the entire index of central Texas native plants are used regularly within landscape applications. This is a huge gap and we need to widen this window of everyday utilization, to bring these plant specimens back into broad usage and increase their associated numbers and acceptance in popular knowledge”. For many native enthusiasts, and use of non-native varieties represents a slippery slope, especially when there are so many that remain underutilized and await diverse implementation. Many times throughout our agricultural history, invasive species have become an ecological scourge when they were originally introduced with good intentions to serve a particular purpose or fill a desirable environmental niche. For central Texas native plant “purists” it remains clear that the use of non-native flora is not an option, especially when ecological conservation and the expanded use of native varieties is the main objective.

A key recurring concept throughout the interview process was the issue of establishment. For most informants, a green roof was considered “established” when vegetative coverage reached at least 80 percent of the rooftop surface and the selected plant communities could survive with minimal supplementary irrigation. Substantial weeding is critical in the first several years of any green roof system, as weeds are opportunistic species that thrive in heavily disturbed (fresh and loose) soil mediums with minimal competition. Persistent weeding gives the desirable plant varieties time to reach considerable size, shade out surrounding soil, and fill in the root zone of the soil substrate in order to leave no foothold for weedy invaders, thus allowing a green roof system to achieve 80 percent coverage. It was frequently iterated that complete establishment for green roofs takes between two and three years. However, many informants conceded that this figure is in fact more accurate for in-ground establishment and that in a rooftop environment this process might even take longer.

There are many options for irrigation installation including numerous manual irrigation system choices as well as various types of overhead sprinklers. Overhead systems can dispense large amounts of water over widespread areas, are less expensive and have the benefit of being observable above ground in the event of damage or technical error. However, these systems are far from desirable in the unique climate of central Texas. Manually-based drip systems are the irrigation method of choice for most inventoried green roofs and consist of a series of plastic tubing that run several inches beneath soil level. This method does not waste water due to inefficient placement or evaporation as overhead systems do, allowing for water to be directed specifically to the areas in need while releasing and retaining the moisture within the soil. All green roofs under examination required the installation of an irrigation system, an absolute necessity for system establishment and system survival through extreme drought events. A manual system also permits the manager of the site to turn off the water in times of sufficient rainfall, or to alter the watering rates in times of seasonal and climatic flux.

Irrigation was often cited as one of the most difficult aspects of green roof design. Although manual systems are much more cost effective and efficient, their location beneath the soil surface can create difficult maintenance challenges. Several research participants lamented that it was impossible to know if something had gone wrong or there was a leak present until plants had started to die or there was already considerable structural damage apparent. “In some cases, you don’t even know there’s a problem until the problem is almost too big, too overwhelming to solve.” These connected problematic issues of green roofs, irrigation and leakage, represent the greatest obstacles to roof longevity and also the costliest aspect of rooftop repair. Due to these complications, several critical recommendations were made for proper maintenance and upkeep of this essential aspect of green roof systems. First, all irrigation system components must be inspected regularly, checking for tube integrity to ensure that plastic tubing is not brittle due to sun exposure, that all valves and connections are working properly, and that there are no obvious pooling or curious areas of elevated moisture within the soil medium. If there is a pump and reservoir attached to the system, which is more than likely in any medium-large scale site, the water pressure should be monitored at frequent and regular intervals. Second, there must be extreme care exercised during the installation process. During construction, heavy machinery is employed, a multitude of equipment and materials are moved and shuffled about, and many fabric pins and landscaping staples are driven through the various layers of rooftop components to piece and hold the structure together. It is imperative that throughout this process the waterproof membrane is not breeched, a mistake that could put the entire project in jeopardy before it has even reached completion. Each green roof construction and design team must have a secure margin of error in place and err far on the safe side of this parameter to ensure waterproofing membrane integrity. Finally, to provide for adequate drainage in the event of a leakage incident or that one drainage system is clogged or somehow loses functionality, drainage systems must be redundant. This strategy will provide for continued structural stability and drastically reduce any financial expenditures associated with rooftop repairs.

Numerous informants mentioned several other important considerations, unanticipated consequences or valuable lessons learned with some regularity. Modular "component" systems remain undesirable in our local climate for several reasons. Irrigation of this type of green roof is consistently difficult, the ability to engineer an efficient watering system that can transverse through a complex interwoven tray system. This usually requires the installation of an overhead irrigation method, which again leads to water loss and increased energy use. Additionally, most modular systems are contract grown, creating large numbers of homogenous trays featuring an identical plant composition. This approach does not lend itself to a natural landscape or "wildscape" aesthetic, a mimicry of the surrounding ecosystem and the preeminent appearance most frequently desired by green roof designers and clients. However, considering the diverse goals of any project, there is an "appropriate time and place" and a considerable maintenance advantage associated with this method. As maintenance issues occur or as certain trays of plant die out, they can be easily removed, repaired, replanted or replaced, alleviating the need to excavate and renovate large areas of monolithic green space. Furthermore, modular trays can be removed to provide access paths for maintenance and monitoring solutions, an approach that preserves the ecological integrity of the soil substrate and plant communities from the harmful effects of significant foot traffic.

Although these considerations present aspects that favor the use of modular systems, several ingenious engineering techniques for monolithic green roof design can counterbalance the need for these tactics. Steel grate pathways have become an increasingly popular way of creating access points across green roof sites without compromising the presence of underlying plant species. Low-growing groundcover, sedum and sedge varieties can be planted shale and granite-based mediums 3-6 inches beneath a metal grating walkway, enabling the continuous presence of plant-based coverage while still permitting access points for maintenance and visitation. A specific case that illustrates the unsuitable nature of modular systems within a harsh Texas climate is the green roof located on the Starbucks rooftop of the Escarpment Village shopping center in south Austin. The plastic modular trays of this system have not only proven too shallow to retain sufficient moisture in warmer months of the year, but have also warped, buckled and cracked due to intense sun exposure. This has led to ongoing structural problems, constant costly repairs and poor plant performance. Monolithic green roof systems of insulating and continuous soil substrates have proven to be the foremost option for green roof installation in our regional area.

Interview analysis further illustrated additional lessons learned, including the need for the awareness of strange micro-climate occurrences, such as areas of dense and perpetual shade or high solar reflectivity from windows. These spaces can create an incredibly difficult “death zone” where very little to no plant varieties will flourish, necessitating the use of either very carefully chosen and tested plant varieties or another approach, the use of hard-scape, sculpture or other aesthetic interests. An architectural engineer stressed the importance of considering necessary conveyance methods, both during the original construction process and later roof maintenance. Conveyance methods concern how building materials reach the rooftop, whether it be through industrial crane transportation, the construction of a delegated elevator system within the building, or the use of public access avenues. A case that highlights the technical importance of this consideration is the Dell Children’s Medical Center. Although this location represents one of the largest and most aesthetically beautiful green roofs in the city, there is only one point of access to the rooftop, through the same hallways and elevators used by all attending patients and personnel. This has created a logistical problem of immense proportions, especially in a hospital context where expediency is paramount and the literal health and well being of individuals is at stake. This specific example was cited time and time again by various informants from diverse green roof and conservation professions as a serious lack of oversight and appropriate planning in the design process of green infrastructure.

Green roof professionals encounter a series of frequent challenges in the consultation or planning, design and installation process. One designer stated, “Everything that happens in a rooftop setting is far more acute than anything on ground-level”. Temperatures are much warmer, soil drainage and insulation are drastically altered as opposed to in-ground installation and rooftops are much more difficult to access, creating far more logistical concerns in the construction process as discussed earlier. These issues must be taken into account from the first theoretical conceptions of a project. Additionally, there generally exists a substantial disconnect between actual management requirements and realistic expectations of any eventual desired outcome. It is of critical importance that clear and concise details as well as an exact plan or path toward implementation be established from the very first stages of design, with the input and mutual agreement and understanding of all stakeholders involved, including landscape and structural architects or engineers, horticultural experts, contractors, managers and homeowners. Furthermore, it is essential that participating individuals be educated as to the level of commitment, management oversight and dedication and realistic outcome of every possible expectation, exactly what these expectations require and how these decisions will be executed over the course of time.

This type of coalescence and cooperation amongst diverse interacting parties is a prime example of adaptive cooperative management, a transformative problem solving and management approach to learn and act collectively to systematically adapt to variable change and therefore improve management outcomes (Henry and Frascaria-Lacoste 2011). Every informant engaged through the interview process clearly stated that this is perhaps the single most crucial aspect related to the overall success of green roof design and implementation. To further define a successful green roof system, it is a project that has achieved its particular desired goal, whether it be ecological functionality, pleasing aesthetics, recreational availability or all of the above, while supporting plant communities that can persist in the long-term, an end result of proper plant selection, soil composition and management strategies. Finally, a successful green roof should be capable of adapting and evolving as environmental conditions change, featuring built in resilience that can be found within a natural ecosystem, “a landscape that flexes and provides mimicry of the natural environment, tying the system to the place.” This aspect is especially valuable in times of ecological uncertainty due to the impending effects of global climate change and is again reminiscent of the advantageous possibilities and principles of novel or hybrid ecosystems.

Perceptions, Attitudes and Managerial Motivations of Green Roof Design

Apart from an express desire to successfully match individual project parameters to a specific intentional goal and purpose, there are numerous environmental motivations and ideal industry standards that inspire proponents of green roof design. During the initial design process, it is key to minimize stylistic decisions, focusing primarily on functional decisions that result in successful plant ecology and the provision of environmental benefits for urban communities. For the majority of interview subjects, stormwater management is by far the most significant environmental advantage afforded by green roof development in a densely urban context. On green roof architect commented “The expansion of green roof infrastructure is most valuable in the most flood prone areas of the city, like along the Shoal or Waller Creek watersheds that encompass dense development and high impervious cover ratios.”

Unfortunately, there are several problems associated with foregrounding the importance of this value in the larger conversation surrounding green roof policy and development incentives. First, there is very little research available that quantifies stormwater performance, especially research that compares various types of soil mediums and depth to examine which combinations are most effective in this application. There must be more determination within the industry to quantify and monetize these benefits in order to effectively push the further implementation of green roof systems to address environmental and climate related issues. Secondly, it is hypothesized by numerous green roof architects that in-ground rain gardens may be more effective and less cost prohibitive measures of addressing this same dilemma. However, these projects take up valuable real estate on the ground level and would be in direct competition with Austin's aggressive real estate market. Unfortunately, developers have no incentive to preserve natural lands for public green space of flood mitigation effort. This has prompted several architectural firms to keep a close eye on vacant lots, underused spaces and lots owned by construction companies but not yet developed in order to directly pursue bidding and persistent communication tactics for the greatest possible opportunity to advise and participate in future development decisions.

Other participating informants indicated that ecosystem functionality and ecosystem formation are the most beneficial aspects of green architecture. The primary ecological function within this application is evapotranspiration, the respiratory process of plants that allows for green roof systems to cool the surrounding air ameliorating the UIHE, as well as the soil component's ability to cool the structure underneath. Additional central aspects of management design propose that roofs must be designed to be low maintenance from the very beginning, further reasoning for primarily native and drought tolerant plant installation as well as efficient manual drip irrigation systems. If a design plan calls for significant maintenance and management, it is essential that this is written into the project budget from the original proposal phase, ensuring that the necessary weekly, monthly or annual maintenance is retained and scheduled. It is highly desirable that design and science function together, creating an iterative and holistic approach to the design process. One conservationist offered, "You need to be on the lookout for and take advantage of unintended or accidental species success and composition. If this is occurring in a specific setting or microclimate this can be replicated and provide the basis for the greater use of certain rare species." Furthermore, water collection systems are of significant interest to the green roof industry due their capacity to reduce, reuse and recycle, another excellent example of truly sustainable architecture. Unfortunately, examples of these systems are not yet well represented within the city. To examine each particular green roof site as a whole and to utilize certain features such as greywater and condensate water availability are always highly sought after and preferable strategies for sustainable design solutions.

A final recurring theme that deserves mention is the subject of public policy and green building incentives for the city of Austin. Many cities throughout the country including Denver, San Francisco, Portland, Chicago and Washington D.C. have passed significant green roof building ordinances and offered financial incentives in an attempt to bolster the installation of green and sustainable infrastructure. With the exception of just a few minor tax incentives mostly geared towards large-scale developers, Austin has yet to incentivize any such investment. One informant stated, "Incentives don't build green roofs. Clients build green roofs. That's where the money comes from." It has been suggested that Texans have a basic cultural aversion with mandate policy, perhaps due to a historic association with individualism and individual rights. Many participants stated that legislating green roof development in Austin simply is not a possibility, that attempts to do so only seem to create enemies and an environment more inhospitable to collective task management and collaboration. Two examples of local organizations and incentive programs that seem to approach this development interest in a different fashion are the Sustainable Sites Initiative and Austin's Functional Green. These programs offer incentive points on a voluntary basis, awarding points that can then be submitted for tax or monetary value based on actions that people have taken, rather than punishing people for things they have not done, which is the cornerstone of most ordinance efforts. Hopefully over time, these initiatives will encourage the further use and installation of green roofs and other models of sustainable architecture.

Discussion

Ecological Conservation in Urban Environments

Most ecological studies and conservation efforts focus on the estimated 25-40 percent of the terrestrial biosphere that remains as wildlands, a bias that omits a substantial portion of the globe that has been profoundly altered by human activities (Evers et. al. 2018). Novel landscapes, used interchangeably throughout the literature as hybrid, emergent, anthropogenic, recombinant or no-analog ecosystems, contain new combinations of species that directly arise through human action and intervention, environmental change, and the impacts of the deliberate and inadvertent introduction of species from other regions (Hobbs et. al. 2006). Green roof systems, by their very definition and design, are prime examples of novel and hybrid ecosystems. These ecosystems, in which species change is accompanied by altered function and human interaction, are increasingly likely in many areas across the globe due to the intensity and pace of ecosystem decline (Clement and Standish 2018). At the center of the debate surrounding novel ecosystems is the issue of whether such changes are reversible and if so, how modern conservation and restoration policies and practices should be reformed to deal with these transformative changes (Clement and Standish 2018). Accepting irreversible change and new management objectives challenges fundamental understandings of traditional ecosystem restoration and biodiversity conservation, primarily that of anchoring management goals to historical baselines (Hobbs et. al. 2014). While there are numerous experts in the field that do not outright reject the potential benefits of traditional approaches to nature conservation, concerns are explicitly expressed on the merits of employing a historical reference model for conservation activities in an era distinguished by global environmental change and a continuing trajectory away from previous conditions (Lennon 2015).

Novel ecosystems represent an alternative form of conservation ecology particularly relevant to the urban environment, in which human-social systems and ecological systems are highly integrated. As cities of the world continue to become more densely populated, it is likely that most people's experience of nature will feature novel or hybrid systems, providing some of the most valuable opportunities to connect with nature for a wide cross-section of society (Hobbs et. al. 2014). These concepts further substantiate a driving cultural interest as well as a larger ecological necessity to explore the possible outcomes of green roof installation and changing land management practices in an urban context.

Novel ecosystems provide a multitude of benefits that mirror those of green roofs and urban green infrastructure including health benefits, psychological and spiritual benefits as well as opportunities for education, relaxation and recreation (Standish et. al. 2012). Novel ecosystems are regarded as model examples of ecological resilience for their ability to self-organize, adapt to change and self-evolve in the absence of deliberate human management and manipulation. Novel ecosystems and resilience theory, in contrast to the backward-looking approach of rewilding projects, share a commonality of being oriented towards an unknown, future paradigm, viewed as part of a transitioning and transformative process rather than the end state of a process (Collier 2014). Green roofs possess a unique potential to serve as an exemplary prototype of contemporary conservation, adapting conservation practices to deal with transformative ecosystems and ever-evolving landscapes in the face of rapid change, urban expansion and increased human pressure on the environment (Clement and Standish 2018).

Despite the numerous advantages these emergent ecosystems stand to offer there is considerable criticism regarding several aspects of a broader acceptance and inclusion of novel landscape programs. Some ecologists and others in the restoration ecology community feel that acknowledging the presence of novel ecosystems is counterproductive and a threat to existing policy and management approaches while some see their inclusion in scientific discourse as pulling resources away from high value conservation assets (Hobbs et. al. 2014). A central concern is that accepting the reality of novel ecosystems represents a slippery slope in our commitment to conservation and restoration, opening the doors for invasive species implementation and the diminishment of native, historical landscapes. A key line of contention between these distinct schools of thought is the divergent position of each regarding the ontological status of non-native species (Lennon 2015). For preservation-focused approaches, non-natives are conceived as undesirable human introductions that threaten the intrinsic value of genuine native ecosystems, while those advocating the concept of novel ecosystems contend that native designation is not a sign of evolutionary fitness or guaranteed positive effects (Lennon 2015). Hopefully, novel ecosystems in the form of green roof systems can represent an opportunity for a more dynamic and flexible approach to nature conservation without compromising legitimate management goals of traditional conservation practices.

Public Attitudes, Values and Perceptions of Green Roof Systems

Green roofs are designed in a variety of different ways in order to feature the diverse goals and plant community possibilities of a particular management strategy. As discussed earlier, intensive roof systems are characterized by larger and lusher plant assemblages and may resemble a public park or rooftop garden space while extensive green roofs are much more subtle, typically comprised of native prairie grass or wildflowers species. Prairie-style green roofs have gained considerable popularity as part of the recent trend to mimic the native habitat of an ecoregion. Although this supports ecological restoration goals, it also conflicts with ambiguous preconceptions of urbanites to the aesthetics of “wild” and “messy” nature in the city, partly due to societal expectations of what kind of nature to expect in the city and where it should occur (Loder 2014).

Despite this trending interest in the construction of extensive roof systems, urbanites and those visiting green spaces of urban areas often prefer the aesthetic value of intensive green roofs and the corresponding dramatic display of urban nature (Jungels et. al. 2013). Numerous studies clearly indicate that perennial dominated roofs, ranging from intensive to semi-intensive, consistently receive the highest aesthetic rating while clumping grass and sedum species rate closely behind, popular for their neat, structural appearance (Jungels et. al. 2013, Fernandez-Canero et. al. 2013, Mesimaki et. al. 2017). Some argue that benefits of nature are better associated with a formal landscape setting than with a naturalistic design which can be perceived as highly beautiful in season but can also be perceived as unkept and untidy during the rest of the year (Fernandez-Canero et. al. 2013). People appreciate more natural looking areas but also esteem a more formal appearance in which public green space is clean, well-organized and managed, recalling elements of order and control (Fernandez-Canero et. al. 2013).

Cultural attitudes towards landscapes and urban green space are often shaped by their values, especially environmental values as referenced by the most common benefits associated with green roof systems: support of plant and animal species, energy reduction and rainwater storage (Jungels et. al. 2013). Studies have found that an individual’s education level, socio-demographic characteristics and childhood environmental background substantially influence their preferences towards different types of green roofs and urban green infrastructure (Fernandez-Canero et. al. 3013). The overwhelming majority of cultural perceptions are concerned with the social aspects and benefits green roofs can offer to urban dwellers, representing a significant *biophilic* inclination towards connection with nature. The fluorescence of green roofs and green infrastructure initiatives provide space for a feeling of peace and silence, of entering another world, a sense of safety, allows for scenic views and vistas, and provokes a fascination with wild nature and the larger course of time (Mesimaki et. al. 2017).

Social and Environmental Equity of Green Infrastructure and Sustainability Projects

Current discourses surrounding urban development and the increase of green or sustainable efforts generally discuss the unintended consequences of these issues: gentrification and the displacement of local communities. Although increased investment in green development can certainly provide benefits and economic opportunity to urban populations, negative impacts are possible as well. A process referred to as "environmental gentrification" outlines an ironic likelihood in which sustainability projects, while appearing politically neutral as well as ecologically and socially sensitive, in practice promote the subordination of equity to profit-minded development (Checker 2011). This term describes the convergence of urban development, ecologically minded initiatives and environmental justice activism in an era of advanced capitalism, a neoliberal order in which governments fail to address citizen's most basic needs in order to take on grandiose projects designed to attract global capital (Checker 2011). The advancement of green infrastructure can be an attempt by city governments to align themselves with environmentally-oriented framings of the modern city, symbolic of their apparent values and sustainable intentions (Gabriel 2016).

Additionally, issues of social justice are a critical feature in conversations regarding green development and urban revitalization, primarily with respect to the uneven and inequitable distribution of sustainable development initiatives. Some argue that these seemingly benign urban greening projects perpetuate existing inequalities and are instituted with little attention to historic structures of erasure, institutionalized racism and land acquisition (Safransky 2014). Novel landscapes, recombinant wildlands and the "blank slate" potential of green roofs potentially represent a frontier of empty landscapes in need of appropriation, settlement and improvement by non-local actors (Safransky 2014). This is closely related to the term "greenwashing", a process in which potential urban green space in the form of abandoned rooftops, brownfields, wastelands, edge zones, and underused areas are modified to comply with broader public expectations of urban nature and to attract investment capital that manifests in eventual uneven development (Francis and Lorimer 2011).

This concept can be further illustrated through a discussion of another critical aspect of ecosystem services that green roofs can potentially provide, urban agriculture. Urban agriculture refers to the growing, processing and distribution of food and nonfood plant and tree crops and the raising of livestock directly for the urban market, both within and on the fringe of an urban market (Rogers and Hiner 2016). The progressive implementation of urban agriculture within the installation of green roof systems is especially compelling giving increasing global food demands, climate related crop failure and consistent limitations on fresh food access in urban areas (Lin et. al. 2015). As urban landscapes are typically highly simplified and intensely developed systems with low levels of biodiversity, urban agriculture constitutes an excellent opportunity to increase the biodiversity and associated ecosystem services of the urban environment. Urban agriculture not only allows for a proliferation of vegetative, insect and invertebrate diversity but also contributes to pollination assistance and seed dispersal, natural pest control and regulation, carbon storage and sequestration, and the reduction of impervious surfaces (Lin et. al. 2015).

The benefits of green roofs and the inclusion of urban agriculture within the broader envelope of urban sustainability are immense. However, it is imperative to consider the possibility of associated greenwashing and the development of an elitist niche that benefits only certain population demographics while systematically excluding others. The concept of urban political ecology further informs this concept. Little attention has been paid to the *urban* as a process of socio-ecological *change*, while discussions about global environmental problems and the possibilities for a sustainable future customarily ignore the urban origin of many of these problems, while failing to acknowledge the intimate relationship between the capitalistic urbanization process and socio-environmental injustices (Heynen, Kaika and Swyngedouw 2006). Urban political ecologists ask the question "sustainability for whom," and elucidate that urbanization processes produce uneven results including rapid gentrification, deindustrialization, inadequate informal housing, suburbanization, exurbanization and the restructuring of rural places and economies (McKinnon et. al. 2017). These are important concepts to bear closely in mind relating to any conversation concerning sustainable urban development and to critically assess the intended benefits, beneficiaries and purpose of any particular "green" solution.

Opportunities for Further Research

This research illuminated vast potential topics of interest for further investigation into diverse theoretical and practical applications concerning urban ecological conservation efforts. Traditional conservation methods adhere to an approach of *restoration*, seeking to return ecological communities to a historic baseline, a truly native ecosystem before the influence of humanity and the progression of the modern world. However, where ecosystems have been pushed beyond their historical range of variability, it may not be practical to maintain or restore them to past conditions (Hobbs et. al. 2014). Up to 36 percent of the Earth is considered so drastically altered by human activity that it may not be feasible to be restored to historical referents (Collier 2014). Thus, emerging approaches to conservation promote a strategy of *recombinant* or *reconciliation* ecology, novel or hybrid ecosystems that utilize diverse plant communities and assemblages of unprecedented patterns. These emergent land management practices may have the potential for realizing ecosystem service provision or new cultural or recreational services that were not historically present (Collier 2014). Established regimes of ecological conservation constitute an approach that views nature as static, predictable and fixed at specific points in time and negates the societal and environmental potentials that novel ecosystems can provide (Collier 2014). In contrast, novel ecosystems represent a self-organized and self-directed evolutionary response of nature to human influence and advance a forward-looking perspective that challenges the hegemonic priority afforded historic species composition in nature conservation (Lennon 2016). Due to the increasing and unknown effects of global client change, the shifting ecological distribution of many plant communities and the numerous benefits these ecosystems stand to provide urban communities, novel landscapes represent a valuable opportunity to examine changing methods of ecological conservation in an increasingly urbanized context.

An exploration of Austin, Texas green roof sites and an inventory of their geospatial placement clearly indicates that a spatial inequity and environmental inequality is in fact present within the distribution of green roof structures. Residential green roofs are severely concentrated on the more affluent west side of town and in luxury residential apartments within the downtown business corridor. This spatial evidence demonstrates the potential validity of the argument many have made against green roof systems and associated sustainable development practices, that they are an elitist, exclusive mechanism of greenwashing, entrepreneurial power and gentrification. This argument is further qualified in the existence of a small portion of green roof sites in rapidly gentrifying areas of east Austin, neighborhoods formerly characterized as disenfranchised and undesirable but now quickly becoming some of the most appealing and trendy places for upper-middle class families and young professionals.

This topic deserves further scholarly investigation and must be examined with a research methodology well informed by the concepts of urban political ecology, environmental inequity, environmental justice and urban renewal ramifications.

An additional interesting finding that deserves brief mention is the almost complete lack of urban rooftop agriculture within the city. This study was able to locate only one example present on a single residential rooftop in far west Austin. This represents a disappointing lost opportunity to utilize plentiful rooftop space for the advancement of food security and greater environmental equity throughout the city. Research participants were asked if there were any specific locations they felt were particularly well suited for, or in greater need of green roof installation. Several informants identified the area underneath and around the conjunction of Ben White Blvd. and I-35, an area marked by numerous large box stores, institutional headquarters, hotels and medical buildings. If all these structures were to contain green roof systems, or especially feature rooftop vegetable gardens that provided the option of year-round food production, can one even begin to imagine the incredible implications?

In line with this type of thinking is the idea of patchwork ecology, adjacent or adjoining green space that can promote habitat diversity and "stepping stone" networks for wildlife movement. Also known as ecological land-use complementation, this concept concerns the clustering together of a whole range of different patches of vegetative cover and promotes numerous ecological purposes (Henry and Frascaria-Lacoste 2011). It is still undetermined if green roofs can provide this type of wildlife corridor and biodiverse habitat within a highly fragmented urban matrix. This fascinating and potentially highly beneficial subject certainly warrants closer examination.

Although this research has yielded a current and complete inventory of green roofs throughout the city, there is still considerable research and field work necessary to acquire a complete list of all specific details associated with each individual green roof. This fully realized list would include spatial location, all parties responsible in the design and construction process, an exact profile of soil composition and plant assemblage, soil depth, roofing and drainage components, type of irrigation system present and ongoing maintenance strategy. This study yielded large portions of this information but a complete database of all relevant details for each site is not yet possible. Upon completion, this database component would certainly prove to be a valuable tool for use by the local green roof industry and provide an especially pertinent representation of successful measures and methods of green roof installation within central Texas.

Conclusion

The city of Austin, Texas has experienced tremendous growth over the past several decades and will likely continue to do so at an expeditious rate for years to come. The further development and installation of green roof systems and associated green infrastructure are exemplary methods of sustainable growth practices. These projects offer diverse ecological benefits to the urban environment, many of which provide critical advantages especially related to the possible consequences of global climate change, such as stormwater mitigation and air quality enhancement. These engineering efforts also provide valuable social capital in the form of public green space within a dense urban matrix of concrete and stone, spaces for urban dwellers to enjoy the regenerative capacities and sensory pleasures of nature and the outdoors.

Despite the growing interest in the environmental and social advantages of green roof systems and their increased installation across the city in recent years, there is still a considerable lack of publicly available information concerning the current state of green roof development within Austin, Texas. There is no current research or interactive public forum concerning the diversity of possible motivations for green roof development or the various parameters of ecological success and how this can be more effectively achieved, particularly in the unique climate of central Texas. This research directly addresses this lack of knowledge and contributes to a more robust understanding of green roof development within the city by creating a comprehensive and current inventory and geospatial database of Austin's green roof landscape. This valuable visual representation displays all residential, commercial and institutional green roof projects within and the city while corresponding informal interviews and field research have examined more detailed questions concerning this design and development inflorescence: What motivates and inspires green roof design? How do these engineered ecosystems benefit the social and environmental networks in which they are located? And finally, what distinct elements or combination of characteristics contribute to the long-term establishment of ecologically viable and aesthetically beautiful green roof systems?

To answer these questions, data collection and data analysis were conducted for each essential aspect of this project: the collection of a green roof inventory as well as sequences of informal interviews to explore individual preferences, management decisions and various measures of success or failure. This project was able to identify a total of 58 green roof systems across the city, a substantial increase from either published inventory previously available to the public. Green roof development is severely concentrated within the downtown business district, an architectural status symbol of many downtown luxury apartments and elite office buildings. Green roofs across the city are dominated by primarily native plant profiles, showcasing plant species that perform well in this unique bioregion characterized by excessive heat and prolonged drought as well as severe flooding events. Residential green roofs are commonly found on multi-family apartment buildings but are also well represented on single-family homes. However, the majority of these examples are owned and maintained by more affluent demographics, unfortunately situating private green roof development as an exclusive hobby for the rich or privileged. However, extensive green roofs represent most green roof systems within the city. These green roofs are easier to install, easier to maintain and are far more cost efficient, qualifying them for use in an incredibly diverse array of applications. It is these types of green roofs that will hopefully experience dramatic increased use and installation while situating green roof development as an inclusive ecosystem service for the enjoyment of all citizens of Austin, Texas.

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Appendix

Table 1. *Mapped variables for the collection of the green roof inventory and spatial database.*

Data Category	Mapped Variable	Frequency	Percentage
Green Roof Type	Intensive Extensive Semi-intensive	3 30 25	5% 52% 43%
Plant Assemblage	Native Native/Non-native Blend	32 26	55% 45%
Building Type	Institutional Residential Commercial Green Space	12 31 11 4	21% 53% *Single-family dwelling – (14) 45%* *Multi-family apartment – (17) 55%* 19% 7%
Site Source	Watershed Protection Dept. Current Inventory	16 42	28% 72%
Total		58	100%

Table 2. *Inventoried green roofs and locations.*

Building or Residence	**Address or Street Intersection**
Ladybird Johnson Wildflower Center	4801 LaCrosse Avenue, 78739
Austin City Hall	301 W. 2nd Street, 78701
Austonian Condominiums	200 Congress Avenue, 78701
Dell Children's Medical Center	4900 Mueller Boulevard, 78723
Escarpment Village (Starbucks)	5800 W. Slaughter Lane, 78749
Ronald McDonald House	1315 Barbara Jordan Boulevard, 78723
Whole Foods Market Headquarters	Exposition and Mountain Laurel Lane, 78703
Jefferson 26 (Student Housing)	2600 W. 26th Street, 78705
Montgomery House (Student Housing)	2700 Nueces Street, 78705
Cameron House (Student Housing)	2707 Rio Grande, 78705
Sterling House (Student Housing)	709 W 22nd Street, 78705
Texas State Capital	1100 Congress Avenue, 78701
Spring Condominiums	300 Bowie Street, 78703
Shore Condominiums	603 Davis Street, 78701
Great Outdoors Nursery	2730 S. Congress Avenue, 78704
Crescent Riverside	127 E. Riverside Drive, 78704
Hill Country Residence	Escarpment Blvd. and Redmond Rd., 78739
Stanley Studio	1901 E. M. Franklin Avenue, 78723
Edgeland House Residence	Red Bluff Road and Shady Lane, 78702
Boyter Residence	5125 Bruning Avenue, 78751
Cuernavaca Residence #1	Lakeridge Drive and Lisa Drive, 78733

Cuernavaca Residence #2	Mecca Drive and Tonto Lane, 78733
Rhode Residence	808 Dawson Road, 78704
Scenic Residence	Scenic Drive and River Road, 78703
Westlake Hills Residence	Redbud Trail and Kennan Road, 78746
Cloverleaf Residence	Cloverleaf Drive and Berkman Drive, 78723
Fidelity House Residence	Toro Canyon Road and Christopher Drive, 78746
Tarrytown Residence	2412 McCall Road, 78703
Peninsula Residence	Hudson Bend Road and Doss Road, 78734
Rooftop Veggie Garden	Pecos Street and Warren Street, 78703
Austin Public Library	710 W. Cesar Chavez, 78701
UT Student Center	2201 Speedway, 78712
Shoal Creek Walk	835 W. 6th Street, 78703
The Northshore	110 San Antonio Street, 78701
Congress Tower	816 Congress Avenue, 78701
Corazon Apartments	1000 E. 5th Street, 78702
Gables Park Towers	111 Sandra Muraida Way, 78703
Lamar Union	1100 S. Lamar Boulevard, 78704
Hotel Van Zandt	605 Davis Street, 78701
Fairmont Hotel	101 Red River Street, 78701
Norwood Towers	114 W. 7th Street, 78701
University House	2100 San Antonio Street, 78705
7East Apartments	2025 E. 7th Street, 78705
SEVEN Apartments	615 W. 7th Street, 78701
South Congress Hotel	1603 S. Congress Avenue, 78704
Google Gates Building	500 W. 2nd Street, 78701
UT Dell Medical School	1601 Trinity Street, 78712
Oracle Waterfront Building	2300 Cloud Way, 78741
John Gaines Park	2708 Sorin Street, 78723
GROWERS Bus Stop	5707 Manor Road, 78723
Springdale Bus Stop	Springdale and Glissman Road, 78723
Palisades Apartments	6300 Bee Caves Road, 78746
Livestrong Foundation Headquarters	2201 E. 6th Street, 78702
Capitol Complex Master Plan	1601 Congress Avenue, 78701
Austin Towers	900 S. 1st Street, 78704
Historic Seaholm Power Plant	800 W. Cesar Chavez, 78701
South X Southwest Headquarters	1400 Lavaca Street, 78701
The Domain	11410 Century Oaks Terrace, 78753

Figure 1. *Current Green Roofs of Austin, Texas. The original 16 previously available to public are visible in red. The additional 42 included in this project are featured in green.*

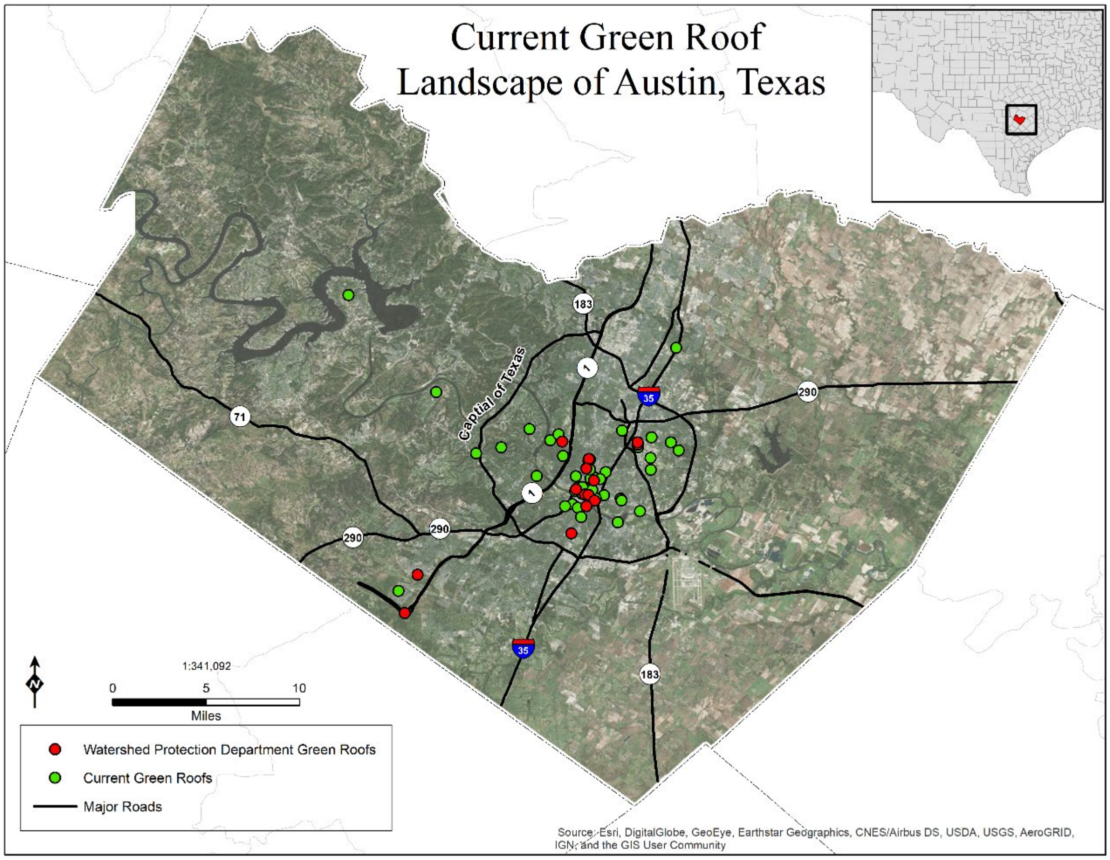


Figure 2. *Inset of green roofs located in downtown business district.*

Figure 3. *Green roof building categories. Note: The residential marker symbolizes both single and multi-family dwellings. Please refer to Table 1 for an accurate percentage of these distinct variables.*

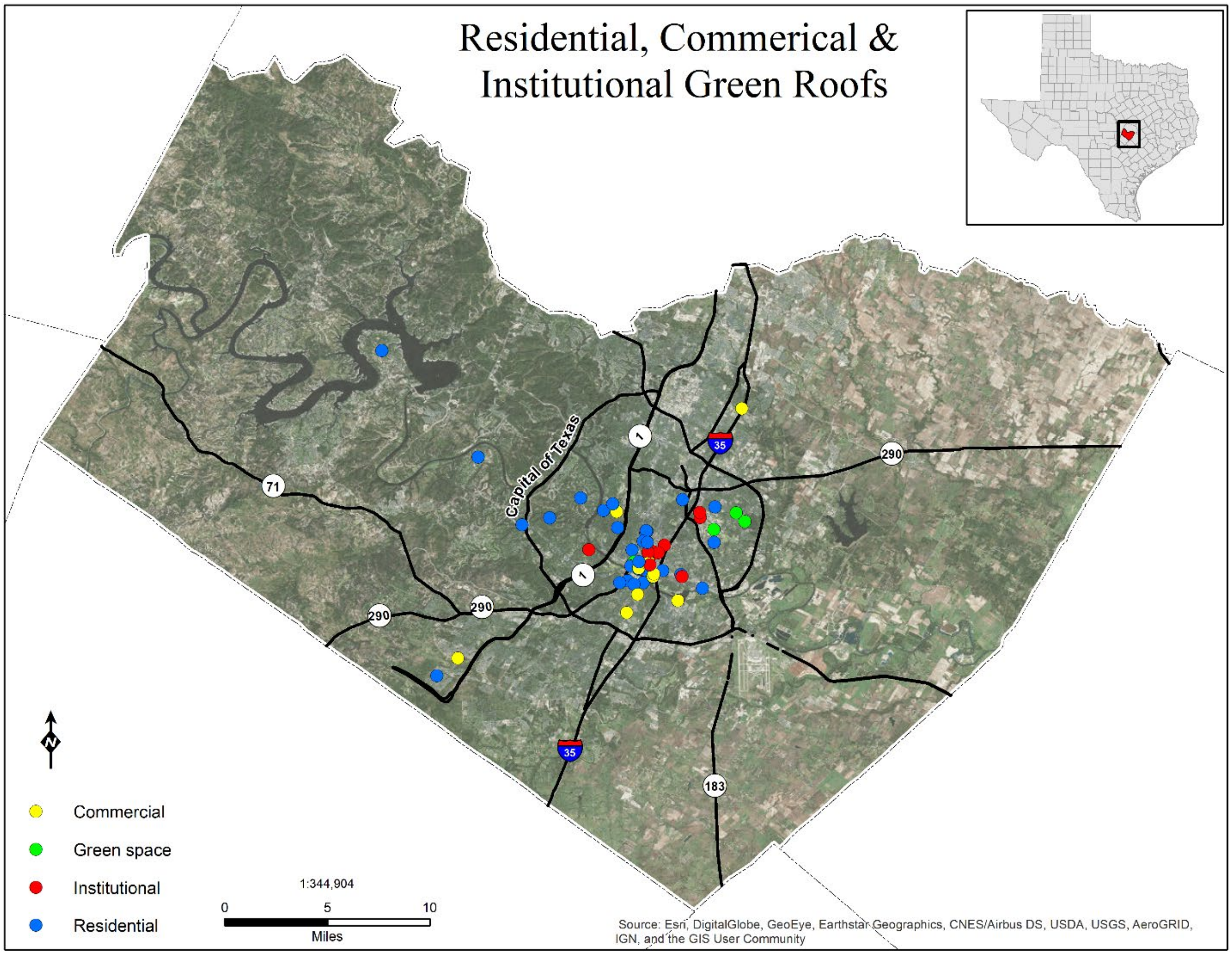


Figure 4. *Green roof types. Note: There are only 3 intensive green roofs in the city. See additional available inset.*

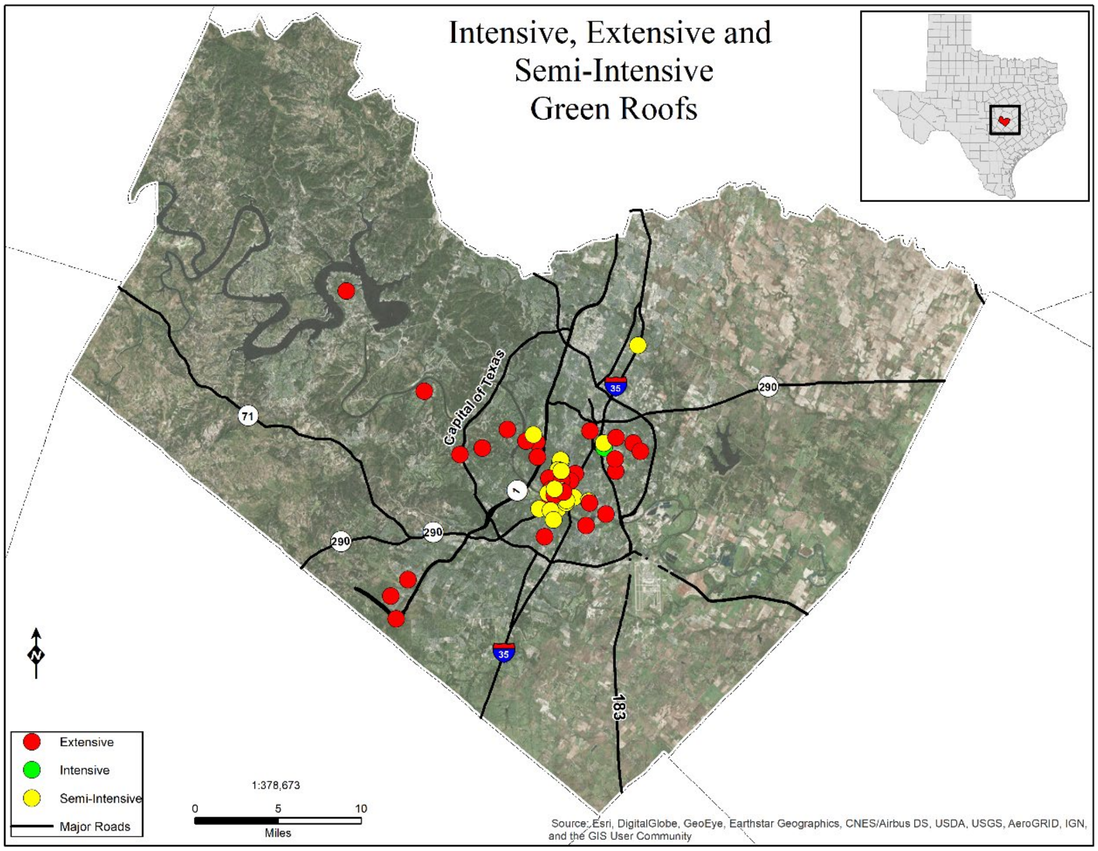


Figure 5. *Downtown intensive green roofs featured in green.*

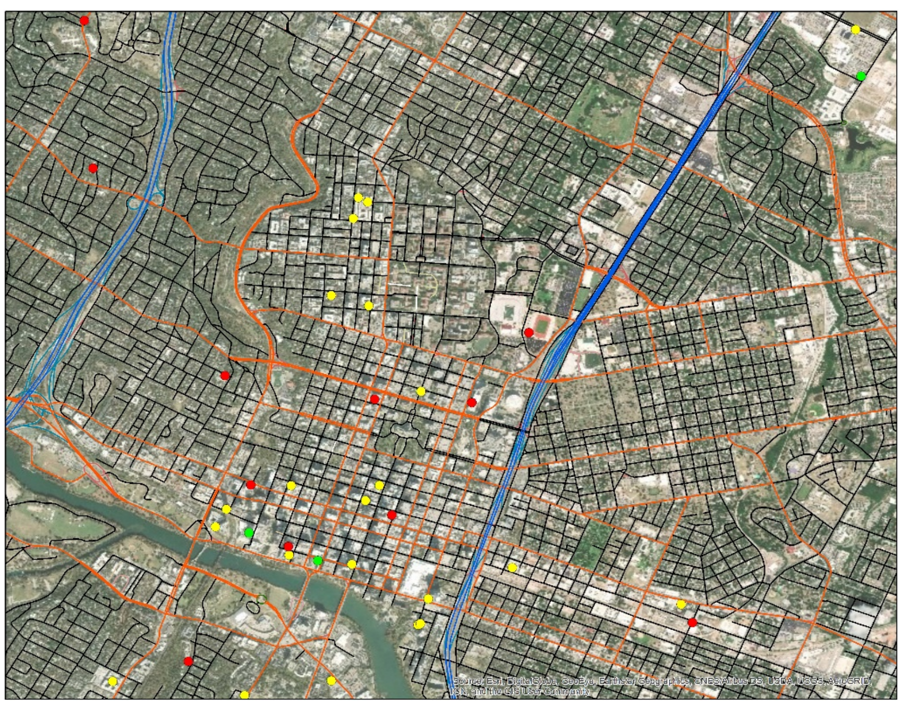
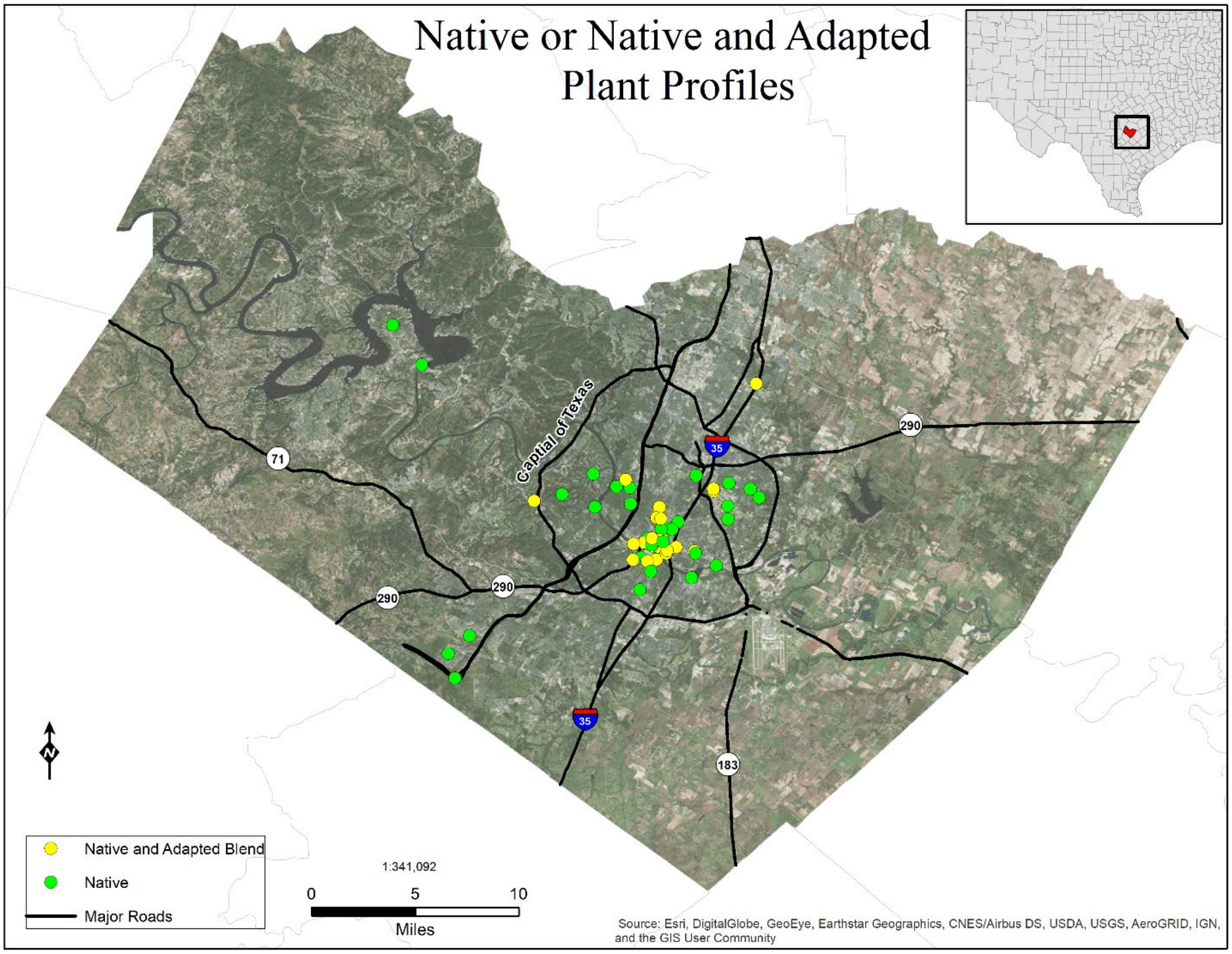


Figure 6. *Roofs featuring a native plant pallet or a native and adapted blend of plant species.*



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