DEFINING AND MEASURING GREEN ROOF FAILURE USING A CASE STUDY OF INCENTIVIZED INDUSTRIAL, COMMERCIAL, AND INSTITUTIONAL VEGETATED ROOFS IN PORTLAND, OREGON

by

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ABSTRACT

Defining and Measuring Green Roof Failure*
Using a Case Study of Incentivized Industrial, Commercial, and Institutional
Vegetated Roofs in Portland, Oregon

R. A. Thurston

Utility agencies obtain publicly valued ecosystem services by incentivizing installation of externally managed green roofs (GRs). GRs provide decentralized “green” infrastructure, but don’t receive asset management like centralized pipes and pumps, which constitute “grey” infrastructure assets. A GR failure baseline is similarly not defined or measured. This research establishes unprecedented operational definitions of GR failure obtained by surveying 44 GR-expert utility representatives, planners, product providers, contractors, owners, managers, and owner representatives. Application of resulting “partial,” “total,” and “catastrophic” failure categories to a case study sample of Portland, Oregon’s GRs demonstrates how criteria are assigned by GR interest groups and highlights varied failure criteria. A second survey involving 52 industrial, commercial, and institutional owners, managers, or representatives of Portland GRs revealed a broader range of partial and total failure issues than identified by industry and agency interests. Both surveys’ failures fall within a three-tier progression of failure criteria, including “total and catastrophic” (GR removal, regardless of cause or interest affiliation) and several types of “partial” failures. Portland data implies a total GR failure that averages 2.94% per year. However, when compared to expert-defined criteria, industry- and owner-defined total failures in Portland averaged 20.17% per year (6.37% of the total) and partial failures averaged 8.82% per year (representing 36.54% of the 52 sites surveyed). When untreated, the latter potentially manifest in total failures. Acknowledgement of a wider range of client interests may support a higher rate of successful GR installations than the overall 3% of total rooftop area in Portland, a rate achieved after nearly two decades of GR incentives. Replication of failure analysis would strengthen the data toward fulfillment of all interests’ needed benefit returns. Research implies that agencies incentivizing green infrastructure would also benefit from cradle to grave life-cycle cost analyses that broadly compare both “grey” and “green” infrastructure options.

Keywords: *failure, roof, green roof, ecoroof, eco-roof, vegetation, stormwater, infrastructure, municipal utility(ies), industry, consumer(s), ecosystem services, best management practices (BMPs), asset management, climate change*

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List of Abbreviations

(see Appendix A for a Glossary of Terms)

BMP – Best Management Practices

CBA – Cost Benefit Analysis

COP / BES – City of Portland / Bureau of Environmental Services

CSO – Combined Sewer Overflow

ER – Ecoroof

ET – Evapotranspiration

GR – Green Roof

GrIS – Green Infrastructure

GRHC – Green Roofs for Healthy Cities

LBC – Living Building Challenge

LCCA – Life Cycle Cost Analysis

LEED – Leadership in Energy and Environmental Design

ROI – Return on Investment

UHI – Urban Heat Island

WTP – Willingness to Pay

Chapter 1 - Introduction

Statement of the Problem

Green roofs (GRs, also referred to in this thesis as vegetated roofs or "ecoroofs")[1] are cost-attractive amenities pursued by a variety of interest groups, including utility agencies, ecologists, consumers, and industry interests. Among a trend-driven variety of green infrastructure (GrIS)[2] technologies which includes cisterns, rain barrels, rain gardens, bioswales, green walls and light impact development, GRs occupy a sustainable building sector that can enhance a municipality's climate change resilience through the provision of urban ecosystem services. Installation of GRs also represents a niche market among GrIS options that are dependent on public sector incentives (GSA, 2011; International Green Roof Assoc., 2016; Peck, 2016). With additional financial and, increasingly, regulatory support of municipal utility incentives, the rate of installations has grown substantially in North America and worldwide since the 1970s (GRHC, 2012, 2013, 2014, 2015). However, because the upfront cost of GR technologies remains high (Chao, 2014), the industry remains dependent upon incentives for continued industry growth.

From a cost to build and install perspective, GRs are specifically proven to be more cost-effective than expanding the conventional drainage and stormwater treatment systems known as grey infrastructure (Cardno TEC, 2012; Carter & Keeler, 2008; City of Portland Bureau of Environmental Services (COP/BES), 2012; EcoMetrix Solutions Group, 2014; IGRA, 2016; Shepard, 2010). As a result, the GR industry and agencies behind GR installation have an

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[1] For readers interested in understanding the complexities of GRs and how they factor into GR failure, an overview of GR technologies and related details is offered in *Chapter 2 – Thesis Definitions*.

[2] see the Glossary in Appendix A for an overview of terms used in the thesis

interest in consumer participation. Are consumers willing to pay to become keepers of private assets that provide public utility infrastructure? What is consumer willingness in the midst of many unknown risks?

The problem is multi-pronged. First is an apparent lack of criteria for measurement of long-term GR failure—or it's opposite, success. If this appearance is mistaken and there are operational failure definitions, they are not evident and are therefore subject to inconsistent application.

Lack of failure definitions underlies the second issue: a lack of failure analysis and related data, which creates a non-uniform process by which consumers, agencies, ecologists and industry interests might measure GR failure. Lack of post-installation data ultimately undermines true assessments of potential benefits provided by GRs.

A third issue and outcome associated with the lack of failure criteria and resulting lack of data collection is a lack of effective asset management. Although utility agencies use publicly funded green infrastructure (GrIS) such as GRs to replace and/or expand the capacity of aging infrastructure assets, follow-up asset management of externally engineered GRs, if any is provided, becomes the responsibility of property owners (City of Portland, 2008; Russo et al., 2006). Lacking standardized upkeep after installation, GRs tend go without the kind of maintenance inputs applied to standard brick-and-mortar assets. GR failure according to owner criteria that are different from agency criteria can mean removal of important GR assets.

A fourth issue area that is tangential to the thesis but important to the interests that hope to reinvigorate the installation of vegetative roofs is consumer and industry understanding of and access to localized horticulture guides and best management practices (BMPs) specific to GRs. These details appear to be limited, in part, by the lack of agency GR failure criteria and failure data. Failure data informs consumer risk assessment prior to purchase, and long-term owner-driven GR management that can extend the value of the municipality's infrastructure. Since owners are expected to manage their own GRs, consumer horticultural advocacy enables more success in long term GR management, while undermining GR failures.

All interest groups would gain insight into many aspects of GRs if they could examine even piecemeal historic and baseline GR failure data that has accumulated over the five decades that this form of GrIS has been pursued by utility agencies worldwide.

Why Is Asset Management Analysis Needed?

Asset management analysis is standard operating procedure in aerospace, automotive, chemical, computer software, construction, and defense, among other industries. Use of failure definitions and performance failure baselines by these industries demonstrates how they enhance safety, aesthetics, efficiency, installation, maintenance, and major refurbishment decisions toward higher profits (Brown & Falk, 2016; Francfort, Karner, Harkins, & Tardiolo, 2006; Goodhead, Farrow, & Hughes, 2016; Hect, 2011).

Asset management of conventional roofing installations provides examples closer to GRs in form and purpose (Guggemos, 2006; Mullen, 2015) and suggests that post-installation GR failure data could more reliably inform life-cycle cost analyses than industry assessments that currently reference fewer than 30 installed sites (Peck & Kuhn, 2001), or which reference exemplary but controlled replications obtained in academic settings (VanWoert et al., 2005).

Asset Management Challenges

Unlike asset management for traditional grey infrastructure, utility agencies generally maintain limited GR data and otherwise lack GrIS performance data that measures post-installation GR failure beyond the incentives they have provided (Center for Technology & American Rivers, 2010). Similarly limited in measure are other in-situ benefits that public or private GR assets are claimed to provide (Howe, 2016). Neither does data generally provided by public agencies track whether or not incentivized GRs are still in place to provide ongoing ecosystem services as originally funded, and accordingly, why GRs may have been removed.

Replicable data are needed to confirm or negate academically researched ex-situ environmental, financial, and psychological returns on costly GR investments, to highlight the most effective GR technologies, and to provide a baseline for improvements in GR systems and their-long term management. Such data would substantiate GR life-cycle cost analyses (LCCA), as is recommended for standard roofing installations (Mullen, 2015). GR failure data is also needed to provide comparative life-cycle costs associated with both “grey” and “green” infrastructure options.

Portland, Oregon, which serves as a case study for the thesis, exemplifies the trade-offs associated with the current lack of GrIS/GR failure criteria and asset accounting. While the application of GRs appears to make intuitive sense, operational failure definitions for GRs and associated failure data do not appear to be used by agencies like Portland that incentivize GRs, or by GrIS experts for other GrIS applications. Neither are standardized operational definitions of GR failure and failure rates currently evident in municipal utility or GR industry resources, or in academic literature.

When Asset Management is Missing

Where asset management failure criteria that details a municipality’s GR inventory, condition, and replacement value is missing, agency reporting cannot provide balanced insights into an agency’s overall infrastructure (City of Portland [Bureau of Planning and Sustainability], 2016). Without post-installation performance (including failure) data at the agency level, attempts to basic audits of infrastructure management are short-circuited (Caballero, Kahn, & Prinz [Portland City Auditor], 2016; Leurig, 2013). Forward-thinking efforts of urban planners and other public and private GR-industry interests to address urban resilience issues in the face of climate change are also undermined (Hart/GRiT 2016). The same lack of program transparency can alternately encourage litigation by citizen ratepayer organizations, such as WATR, which challenged Portland, Oregon's use of public funds for green infrastructure in 2011 and 2013.

Lack of effective GR asset management also contributes to less obvious environmental costs. These externalized costs are a less tangible result of failed GRs in terms of solid waste created, lack of habitat created, and opportunities for carbon sequestration delayed. Social costs similarly include a shrinking GR industry and job market associated with rate-payer-funded agency programs that have gained limited market penetration and insufficient numbers of GR installations. Industry and owner interests are further affected when negatively biased reporting of GR failures in public media influences resale of structures that include GRs or minimizes consumer interest in GRs as a sustainable development option (Bloomquist, 2012).

> *You can learn more from failure than from success. In failure, you're forced to find out what part did not work. But in success, you can believe everything you did was great, when in fact some parts may not have worked at all. Failure forces you to face reality.*
>
> — Fred Brooks (Kevin Kelly interview, *Wired* magazine, August 2010, p. 92)

Purpose of the Study

This thesis is designed to investigate whether a known operational definition of GR failure exists. If not, to provide one or more definitions for GR failure and to determine the implications of the results. As such, this is the first systematic investigation of the criteria for GR failure to be used in infrastructure assessment, return on consumer investment analysis, and industry product and service enhancement.

Development and application of standardized operational definitions of GR failure: 1) allows measurement of GR failure and success; 2) enhances development and implementation of agency incentives; 3) informs the enhancement of GR industry products, services, and BMPs within the industry; 4) facilitates informed consumer purchases of GR products, services, and BMPs; and 5) increases the resilience of urban infrastructures that increasingly rely upon the ecosystem services provided by GrIS technologies such as GRs. Any entity with an interest in GRs may gain from the answers provided, whether owner, agency, industry, or education representative.

Study Significance and Context

Pursuit of urban resilience via green infrastructure (GrIS) in North America is rooted in the EPA's enactment of the Clean Water Act in 1972 and 1977 as a result of stormwater and other pollution from urban areas. The continued pursuit of this legislation is largely driven by the need to offset continued pressures of population growth and development density in urban areas, and climate changes becoming manifest (Mechler, Hochrainer, Aaheim, Salen, & Wreford, 2010). GrIS that addresses stormwater management issues include GRs, the use of which as a form of sustainable infrastructure first gained market traction in Europe in the 1970s (Werthmann, 2007), and has since the 1980s has been globally adopted.

Portland City management exemplifies resilience planning that incorporates GrIS to address current and future effects of climate change. The City's planning documents (City of Portland [Bureau of Planning and Sustainability] 2016a) reveal application of green and grey infrastructure to meet ongoing demands of population growth without compromising economic prosperity, citizen equality, or quality of life. City managers have also expressed interest in the enhancement of investment choices via asset management (City of Portland [Asset Managers Group], 2015).

Failure analysis and related asset management of GRs would not have been possible at the outset of Portland's GR incentive program in 1990 without a representative population of installations against which to measure success or failure. Collection and application of post-installation data regarding GRs in other locations around the world has been also been hampered by language barriers (Philippi, 2005). Fifteen years of accumulated GR installation data, as provided by the City of Portland Bureau of Environmental Services (COP/BES, 2010), now makes failure analysis in league with the development of failure criteria possible.

Worldwide, and particularly in North America, GR industry development has been supported by municipal and utility agency incentives to fulfill resilience goals similar to those in Portland, Oregon. This expansion has occurred via pursuit of certification credits that prescribe incorporation of GRs and other technologies into all levels of construction and development projects. Frequently displayed credits are available via sustainability marketing and certification campaigns, such as LEEDs in North America, BREEAM in Europe (Shepard, 2010), or the internationally applied Living Building Challenge. The addition of a nominally sized GR, for example, can make the difference in having a project certified at a higher level. Higher levels of certification not only confer greater symbolic achievement, but can lead to a significant long-term return on investment (ROI) when incentives fast-track a developer's project and/or allow a larger, taller building.

However, although certification programs prescribe and measure the use of pre-completion products, they generally don't pursue post-installation asset management data that this thesis considers (Cassidy, 2016). Some sustainability advocates suggest that market penetration of less than 20% is inadequate given the time and financial resources invested in these campaigns to date, preferring to push for the need of broader market reforms (Cassidy, 2016; Yudelson, 2016). Given marginal market penetration – often less than 5%, development of failure criteria and associated failure rates using agency-provided data may provide one type of beneficial insight toward beneficial reform.

Thesis pursuit of operational definitions and rates of GR failure might answer whether, or not, the City of Portland and municipalities like it, could similarly achieve a better rate of GR market transformation. Understanding failures could help unlock a steadier stream of beneficial GR installations, meeting the intentions and expectations of GR owners and managers—or address the reasons for lackluster adoption of GR technologies.

Research Methodology

This section of the thesis provides an overview of the research involved with the overall development, implementation, and analysis of the thesis, which involves a two-survey, mixed method approach. The first survey asks green roof (GR) experts, worldwide, to define GR failure and confirm the potential association of 34 issues with GR failure. This convenience survey sample includes representatives of utility agencies providing green infrastructure incentives, GR industry educators, providers and practitioners; as well as GR representatives of several large public GR installations. Expert-derived definitions are then compared with issues highlighted by a second survey of owners and managers of commercial, industrial and institutional (ICI) GRs installed between 1985 and 2016 and located in the City of Portland, Oregon. The second survey sample includes 52 respondent who represent nearly 26 percent of Portland's 204 ICI GRs from a total population of over 500 GRs (list provided by Portland's Bureau of Environmental Services (COP/BES, 2010)). In addition to the comparison, the second survey measures each respondent's hypothetical willingness to pay (WTP) for a future GR using Likert scales. For both surveys, coded responses disaggregate GR failure into categories of GR failure initially identified by experts in Survey #1.

Thesis Outline and Considerations

Following Chapter 1, the thesis is divided into sections that address the thesis research process and analysis of survey results that comprise the thesis research. Chapter 2 includes an overview of the types of GRs and the benefits that they sometimes confer; an overview of current GR technologies, including distinctions between them; and an introduction to the players involved in all aspects of GR installations.

In the interest of creating an operational definition, failure is divided into hypothetical "non-failure," "partial failure," "total failure," and "catastrophic failure" categories. This pursuit establishes preliminary differences between levels of failure seen in GRs. These distinctions are applied to expert GR interest groups identified among the experts surveyed. Subsequently, the same distinctions are applied and compared to Portland's ICI GR owners, managers, or their representatives to clarify their perspectives regarding GR failure while providing a test application for the definition generated from expert input.

The literature review in Chapter 3 addresses the current lack of operational failure definitions, as well as other sources that provide a basis for measured GR failure and success. This chapter also references types of failure known to other industries. It lastly introduces a variety of causal agents that enable GR failure.

In Chapter 4, the thesis examines the findings of the two surveys, with the research related to each divided into separate parts. As noted, the first survey asks GR experts situated worldwide to share their perspectives regarding failure in vegetative roofing. Chapter 4, Part I, develops an operational definition of GR failure based upon the surveyed perspectives of GR experts representing public agencies, the GR industry, and GR consumers.

In Chapter 4, Part II, the failure criteria derived from Survey #1 are applied to the results of the second noted survey among the people who manage the population of GRs in the case study municipality of Portland, Oregon. This survey measures the rate of GR failure among the city's industrial, commercial, and institutional GRs.

Chapter 5 overlays the results of the two surveys using the failure definition categories established in Chapter 2 and confirmed via the expert survey detailed in Chapter 4, Part I. By soliciting and applying expert perceptions to the development of an operational definition of GR failure, the thesis aggregates expert-defined criteria for GR failure. It then demonstrates the differences in measured failure rates resulting from the use of the GR failure criteria among ICI owners and managers or their surveyed representatives amidst Portland's GRs. The overall process exemplifies how the operational GR failure definitions can inform long-term GR asset management and enhanced GR program marketing.

Independent Review of Surveys

Surveys implemented for this thesis were reviewed by the Evergreen State College Independent Review Board, as required when approaching human subjects. Because neither survey collects from participating respondents "private identifiable information about living human beings," the surveys did not require IRB modification or oversight. The confidential identity of respondents, whose experience and professional involvement with GRs has helped to develop the understanding of failure within the GR industry, has purposefully been maintained unless otherwise permitted. Survey instruments and the data they produce, however, are provided in Appendices B and C.

Limitations of the Study

Applicability of research and confounding variables

The use of Portland, Oregon as a case study made sense because COP/BES data offers a robust and relatively well-recorded accounting of GR installations over a two-decade period. The data and associated findings provide a semi-random convenience sample, although the research on these GRs aims to be relevant to other municipalities incentivizing GRs in North America, specifically for stormwater benefits. Time limits imposed by the thesis process mandated pursuit of what are considered sufficient numbers and quality of surveys that could be further enhanced.

The potential for other limitations exists. Some plant-, media-, and irrigation-related aspects of the thesis findings may not be applicable or representative in different eco-regions because of GR distinctions related to climate variation and use of localized materials. Irrigation, planting media and plant selection, in particular, are germane to the topic of GR failure because the misapplication of these elements in different climates is a significant source of failure (Dvorak & Volder, 2010; Monterusso, Bradley, Rowe, & Rugh, 2005; VanWoert, Rowe, Andresen, Rugh, & Xiao, 2005). Portland's bioregional climate, culture, politics, and economic differences are another point of limitation that is less relevant to the discussion than the importance of the available data. Regional variations that do confound consistent application of GR technologies, such as the need for seasonal irrigation and plant selection, are highlighted in the text.

Efforts have otherwise been made to focus primarily on details that are representative. Further, the thesis focus is often limited to owner and utility infrastructure stormwater benefits over the, sometimes, conflicting benefits of GRs benefiting energy utilities by providing urban heat island (UHI) amelioration and solar PV energy efficiencies.

One notable limitation is the current lack of academic literature addressing the operational definition of GR failure and/or any type of representative failure rate of green roofs in North America. Performance analysis of post-installation GRs is in its infancy, as demonstrated by the recent dates of peer-reviewed GR program analyses (City of Portland Bureau of Environmental Services, 2016)(City of Portland Bureau of Environmental Services, 2016)(City of Portland Bureau of Environmental Services, 2016)(City of Portland Bureau of Environmental Services, 2016)(City of Portland Bureau of Environmental Services, 2016)(City of Portland Bureau of Environmental Services, 2016)(City of Portland Bureau of Environmental

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Author's Disclaimer

The thesis author's interest in sustainable technologies and practices is lifelong, and includes a curiosity in GRs piqued by literature stating that GRs ameliorate climate change. The author is also interested in GRs from a consumer perspective seeking pragmatic private benefits such as increased longevity of the roofs that underlay GRs and year-round aesthetics as characteristics used to promote GRs.

As a long-practicing landscape design-build consultant, the author can also attest to optimistic customers requesting unrealistic low-to-no-maintenance installations. Since the inception and recognition of GRs in North America, the author has wondered about GR maintenance where access is limited by steps or tall freestanding ladders. How does one get up to (and down from) the GR, with equipment, and tools to water, weed, or mow? People involved in GR project planning, and sometimes with maintenance, don't always have the luxury of having to cope with the outcome of the finished installation. Although the author maintains a positively biased interest in sustainability, and GRs in particular, scant failure information addressing technical GR product options and maintenance requirements motivates the author's interests and concern on behalf of GR consumers.

Chapter Summary

Prior to this thesis, there was little effort, or consensus on the need to define or measure GR failure, let alone the methods used in that pursuit. Nor is consistent information currently available on the current or past rates of GR failure associated with incentives provided for GRs among North American municipalities. Regardless of the objectives for installing a GR, one can currently only guess at the rate of relative success or failure, much less the collective or synergistic influence of multiple partial failures on GR life-cycle costs and associated total, or catastrophic failures. Whether or not the green infrastructure role assigned to GRs among a variety of sustainable options is being fulfilled is therefore not entirely known or measured.

By soliciting and applying expert perceptions to an operational definition of GR failure and verifying implicit definitions from available GR installation data, this thesis: 1) aggregates expert- and agency-defined criteria for GR failure; 2) samples GR installations in Portland, Oregon; and 3) demonstrates differences in failure rates resulting from application of all criteria.

"It's fine to celebrate success, but it is more important to heed the lessons of failure."

—Perman, 2006 (quoting Microsoft billionaire Bill Gates)

Chapter 2 - Thesis Definitions

Familiarity with the components used in green roofs (GR) aids in understanding GR failure and success. This chapter offers a superficial overview of GR technologies providing basic details about GR options along with a list of the numerous desirable GR benefits possible. GR maintenance is another subject that affects GR failure and success, but this topic deserves far more attention and research than the thesis allows.

Naming and History of Green Roofs

English language terminology referring to green roofs (GRs, or "greenroofs") includes "ecoroofs," "living roofs," "vegetated roofs," "sod roofs," "cool roofs," "blue roofs," and "brown roofs." Throughout history, humans have emulated nature's features by encouraging or adding vegetation to their structures to gain protection from the elements, while seeking benefits including insulation for colder winter months and cooling during summer heat. The peat, sod, or birch bark roofs of north hemisphere regions are examples that have, for centuries, been constructed of locally available, renewable materials and, given regular maintenance, provide roofing that can last a minimum of 30 to well over 100 years (Dunnett, 2011). Use of these materials fell out of favor with the advent of lumber and metal sheathing, which don't require community participation to construct or maintain. Despite the loss of energy efficiency, among the other environmental services provided by old-world roof options, today's conventional roofs (and GRs) are much easier to maintain (although neither rooftop is maintenance-free).

At the turn of the 20th century In North America, a surge of socially oriented rooftop garden installations lasted through the late 1880s (Werthmann, 2007). Research and development of GR technologies was otherwise a predominantly European-led phenomenon, with Germany dominating the field after having engineered more cost-effective and lighter weight GR components starting around 1960. Since 1970, GR technologies worldwide have modernized, especially in Germany, Sweden, Japan, England, and Greece. Today's GRs are technically similar to primary succession environments because the growing media has been recently disturbed and has not had time to establish a supportive micro biome community (Magill, 2011). GRs otherwise incorporate the growth of plants on top of all types of building rooftops (Osmundson, 2001).

Green Roofs and the North American/Global Economy

Since about 1980, interest in GRs has been driven in North America by industry trends, and by environmental problems related to increasing density of urban populations and accelerating impacts of climate change. At about the same time, the GR trend caught on in Canada, China, and the United States, also because of marketing trends, GR industry advocacy and dedicated research at a number of universities. Among evolving "building envelope" technologies, vegetated rooftops have been hailed as a "key to the global thermostat" (Mazira, via Thompson & Sorvig, 2007; Mazira, 2014). Green buildings, synonymous to some with the idea of energy-efficient buildings, have gained in popularity in the United States over the past several years as options that enable not only energy independence, but also personal and environmental health (Phocas, 2009).

Distinctions Between Sustainable Roofing Options

Separate from the structures, insulation, and waterproof membrane beneath them, GRs consist of membrane protection such as root barriers, drainage systems protected by filtration fabrics or other devices, and, most commonly, shallow depths of planting media that support the growth of perennial or food producing plants. Components are placed on top of the membrane in a layered "veneer" or as separate "tiles." Some GRs have added insulation, if not for energy benefits of the building, to create slope for drainage (blue roofs are an exception to this generalization). GRs periodically include irrigation systems for the sake of plant survival during extended heat spells and/or for UHI reduction.

Costs for and failures of GRs are sometimes mingled with those of the underlying membrane and roofs below them because of their juxtaposition, and because all three are often co-constructed. The confusion can cloud appropriate attribution of failure, as well as effective asset management analysis (personal communication, J. Crumrine, June 22, 2016). Like a GR, the roof beneath a GR can fail due to neglect, poor design, or other unrelated factors. A basic understanding of GRs and roofing is, therefore, necessary to distinguish GRs from the roofs on which they are built.

Among other objective benefits, GRs are promoted as offering protection to a structure's dynamic roofing membrane, thus extending the structural membrane lifespan (Henshell, 2005a). GR professionals often discuss the membrane longevity benefit, as well as concerns regarding the distinction between the roof and the GR. GR success, as measured by the lifespan of a typical roof membrane, is not only dependent upon regular maintenance of both components, but subject to the integrity of the roof engineering and roofing membrane installed beneath the GR (Henshell, 2005a). However, repairing the roof, regardless of the cause of damage, typically requires the removal of some, or all, of a GR. Some professionals consider a GR to be failed if temporary or permanent removal of the GR is required to fix the membrane beneath it (Henshell, 2005a).

Green Roofs: Not Like Other Types of Roofing

What differentiates GRs from the variety of other, similarly purposed roofs and from cool or conventional roofs is support of plants in soil-like media covering the moisture barrier membranes installed on all buildings. membrane coverage issues due to shrink and swell are minimized by lack of UV exposure hidden under GR soil media, and drainage mats. Vegetated rooftops have the capacity to provide numerous other benefits (Clark, Adriaens, & Talbot, 2008; Köhler, 2008; Peck 2001; Peng & Jim, 2015a; Rosenberg, 2012; Spahn, 2004). Many, but not all, GR benefits can occur simultaneously. Additionally, GR benefits are only *potentially* available, not inevitable. Some GR benefits even contradict the outcomes of others. Further, any component of a green roof—or multiple components thereof—has the potential to fail. Figure 1 illustrates a cool roof next to a green roof on the same building.

Figure 1. A cool roof next to an ecoroof in Portland, Oregon.

Green Roof Types and Applications

Visual consideration of GRs enables better understanding of GR types and functions.

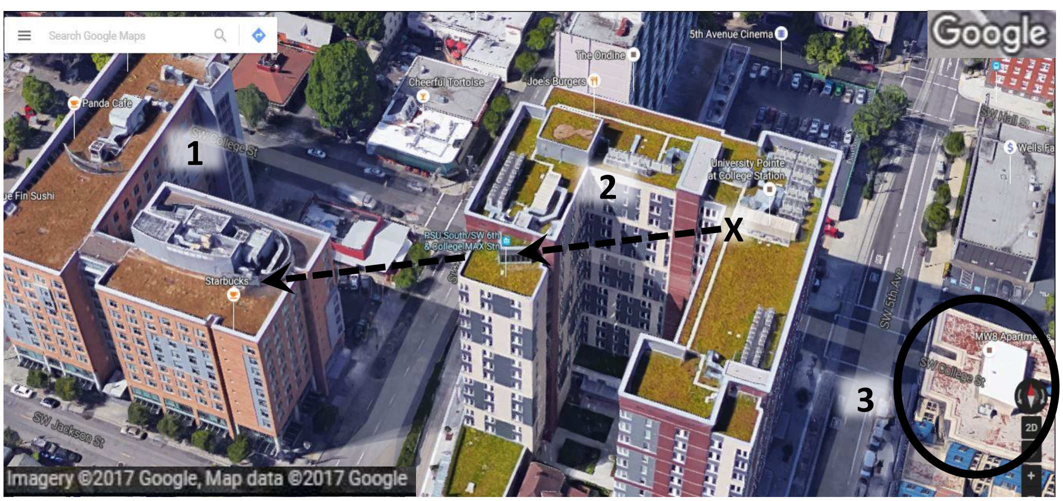


Figure 2. Green roof variations providing different stormwater benefits.

Figure 2 shows three side-by-side extensive veneer system installations in Portland, Oregon, illustrating not only the use of GRs for stormwater abatement, but also the variance of subjectively appreciated or disliked aesthetics that a GR can create. Depending on the time of year, each of the GR installations shown will provide varied amounts of stormwater abatement and filtration of precipitation, among other benefits.

Site #1 (upper left) was installed in 2004 to test stormwater performance. It is mature, dormant, not maintained and is currently unirrigated. Unirrigated, it can absorb more stormwater than site #2 (center), which was installed in 2012. Site #2 is contractually managed to receive up to an inch of water a week from an automated system, 1x/year fertilization and weeding on a 1.5–2x/month basis. As noted by the consultant associated with site #2, irrigation scheduling is decided not by the client, but based on the consultant's professional knowledge (personal communication, J. Crumrine, March 2, 2017). The sedums carpeting this GR provide better UHI benefits to the neighborhood commons than either of the other installations, as well as better energy savings for the building (personal communications, J. Crumrine, June 29, 2016). These benefits result from light reflection, and thus reduced heat absorption associated by the plants, and evapotranspiration (ET) resulting from irrigation of the plants. Site #3 (lower right) was installed in 2013 without irrigation using white volcanic cinders as a planting media rather than the less coarse grit and perlite mixtures used in sites 1 and 2. Research on plant establishment in newly erupted volcanic soils shows that few plants can tolerate these sterile and heat absorbing environments without the aid of michorrizal and organic soil development (Bishop, 2005). The reddish hue of the surviving sedums on this building indicates a drought-stress response, which can attract secondary plant pests that further stress the plantings. As a result, the installation offers limited UHI benefit and thermal insulation to the buildings around and beneath it. The volcanic media, however, does provide an unknown amount of stormwater abatement capacity.

The recently installed facilities manager of site #1 was considering whether to remove the GR because it is considered unaesthetic and a fire hazard (disproven as per Breuning, 2008). This political process illustrates a chicken/egg syndrome in terms of which comes first: the funding or the maintenance. Site #3 was also said by its surveyed representative to be "in need of refurbishment" (personal communications, S. Billings, August 22, 2016, and D. Mendenhall, September 6, 2016, respectively).

None of these installations are physically accessible to the building occupants, a factor that diminishes the impetus a developer or owner might have in wanting a greener aesthetic. However, visual "access" by the occupants of the taller site (#2, as shown in Figure 3; image taken from the "x" noted in Figure 2) might suggest that higher rents could be charged for occupants of rooms that look onto buildings #1 and #3. As noted, however, some people think the dormant look conveys failure. "Which view is more aesthetic?" becomes an operative question that provides opportunity for further analysis than the recently published willingness to pay thesis (Bloomquist, 2012), which similarly examines GRs in Portland, Oregon,.

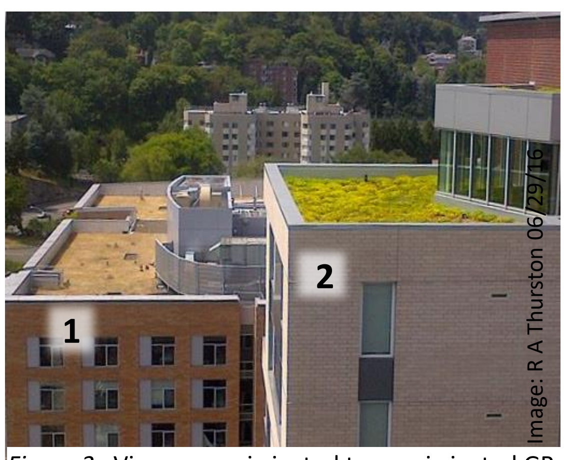


Figure 3. View across irrigated to non-irrigated GR.

All three installations provide stormwater abatement needed by the City of Portland. The volume of water storage each might provide, however, is theoretically different during the drier summer months experienced in the Portland, Oregon, eco-region. The winter stormwater-holding capacity of each GR is also theoretically different, and both values deserve more research in varied locations, with varied plantings and planting media. A similar but less well known GR ecosystem service that benefits the common is carbon sequestration, the need for which will increase in urgency as atmospheric carbon levels continue to increase (IPCC, 2012; Mechler et al., 2010; The Risky Business Project, 2014).

Some GRs provide little to no value from the sustainability perspective of stormwater management or energy savings, but do provide promotional values, as illustrated by the entry GR at the New Seasons Market in Portland, Oregon (Figure 4). In addition to providing an attractive visual guide toward the building entry, this GR is being used as a social marketing tool to convey the owner’s environmental values. It should be noted that representatives of New Seasons had mixed feelings about the value of their installed GRs and were undecided about whether they would continue adding GRs to future facilities because of the costs associated with GR installation and maintenance (personal communications, S. Kellog, August 24, 2016).

Figure 4. Promotional green roof.

Figure 5. Twilight on a high-end intensive GR.

Similar, yet different from the promotional GR in Figure 4, are installations accessible to building occupants, as exemplified in Figure 5. Luxury GRs generally provide a high return on investment (ROI) from tenant leases, depending upon the quality and all- season amenities of the GR installed. Such an ROI is possible despite the ongoing, high-skill maintenance these installations typically require, often including solid-state irrigation systems and daily or weekly management. Many of Portland's high-end waterfront condominiums are plant-clad, LEEDs-certified structures that command nearly triple the standard rent for apartments that range in size from 300 to 1,000 square feet. GRs aren't the only factor driving these prices, but they add to the luxury amenities that these facilities aim to provide to their occupants.

A commonly referenced GR installations in the Portland program literature also promotes Portland as a progressive destination by using selected images of the Multnomah County Amy Joselin ecoroof. As shown in Figure 6, this interpretive demonstration provides seasonally dynamic colors and textures, successfully provided year-round. Like most GR promotional media, these images show the best aspects of the installation, even though it has experienced irrigation and plant failures that are evident using Google Earth ™ and confirmed by the GR manager (personal communications, A Proffitt, February 5, 2016).

According to the online project report (COP/BES, 2004), the irrigated GR cost $15.11 per square foot, which includes the use of a crane to hoist materials to the roof of the fourth floor installation. The project received mixed financing, with $50,000 of the project funding provided by the Bureau and the remainder made possible through grants and in-kind donations.

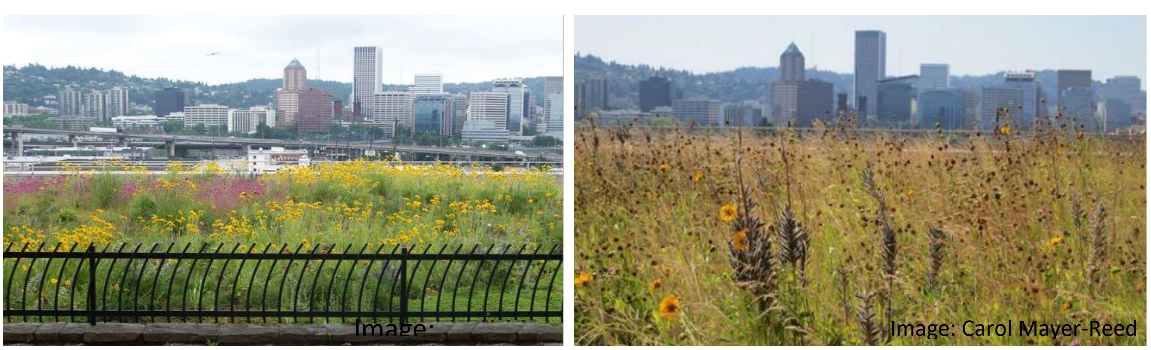


Figure 6. Multnomah County Amy Joselin green roof in summer and fall.

The planting originally hosted more than 15 species of perennials planted in six inches of a proprietary media amidst seeded annuals comprising many more species. A LCCA of the installation estimated a 60-year roofing membrane lifespan. Although the installation is too new to confirm this estimate, the assessment effectively doubles the membrane lifespan in comparison to conventional roofs.

In addition to readily accessible installations, there are also constrained and inaccessible GR installations. Among them is the ecoroof situated atop of the 35-year-old Portland Building. After being buried twice by construction debris, this previously irrigated ecoroof (ER) has undergone two renewals, including a membrane replacement. It may yet be removed when the entire historic postmodern building envelope is renovated to overcome a history of "chronic… compromise and failure." (City of Portland, n.d., para. 3) Many of the web-posted issues mentioned are leaks. This site highlights the logistics and issues involved with the creation of exemplary GR demonstrations.

Figure 7. Hidden urban ecoroofs
Image: Miller/Liptan presentation to GRHC.

The installation in Figure 7 also exemplifies that ecoroofs are not universally appreciated, either by all of an agency's branches, and/or by building occupants. A similar lack of appreciation is noted among public agents whose budget for GR management is limited or nonexistent because a maintenance value was never established before the installation occurred.

Safety with respect to some of the less visible or multi-story GR installations can also present varied challenges, as illustrated in Figure 8. The ladder frame on the left illustrates access limitations to maintenance crews needing to bring mechanical tools to the GR on a regular basis. The unharnessed workers in the image on the right are installing a veneer-sedum mat on a GR. Safety issues create liability, and therefore insurance needs and associated long term costs that add to the equation of an owner's willingness to pay (WTP). The same issues can also hamper the re-sale of a building with a GR.

Figure 8. Safe access to green roofs presents limitations.

In Portland, any size of GR qualifies to expand the stormwater infrastructure (see Figure 9). In addition to installing GRs on all of their own large and small water treatment facilities, City of Portland Bureau of Environmental Services (COP/BES) partners with local developers who provide affordable housing while obtaining funding from federal, state, and local sources for costs associated with ER installations. Maintenance of Portland's own ERs, however, is not a high priority (personal communication, T. Liptan, February 01, 2016, and January 19, 2017; personal communication, C. Cunningham, August 23, 2016).

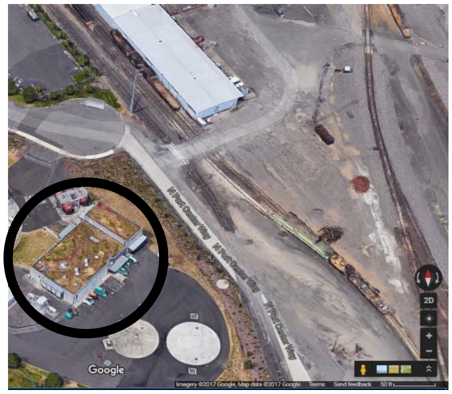


Figure 9. Rooftop sponges in a sea of asphalt.

Figure 10. Moss growing without the aid of planting is a bona fide ecoroof.

Naturally forming GRs qualify as stormwater friendly structures, like the gazebo shown in Figure 10. Although professional roofers are likely to advocate the removal of moss, some will cite anecdotal experience indicating moss protects roofing shingles and membranes from damage caused by sunlight (personal communications, T. Wagner, December 31, 2015). Moss growing passively on shady rooftops, doesn't suffer from drought—it just goes dormant. Similarly, perennial "weeds" may be the long-term outcome of a sun-drenched roof that is allowed to "go to seed." Although unmeasured, natural GRs, such as these, provide relevant stormwater benefits and low-maintenance aesthetics by developing communities of micro-organisms in the rooting zones that enable moss and plants to thrive in these harsh locations.

Ultimately, GRs, like those shown in Figures 2 and 3, feed another question that may evolve from this thesis: "Whose definition of GR failure should prevail?" The answer may be influenced by owner and/or developer economics; driven solely by utility agency needs for a range of public stormwater and/or energy savings benefits, or both interests' pursuit of public and private benefits. Are owners willing to pay for the installation and management of common benefits? This thesis begins to provide replicable data regarding establishment of which interest's need has the most important and/or enduring impact.

General Green Roof Options

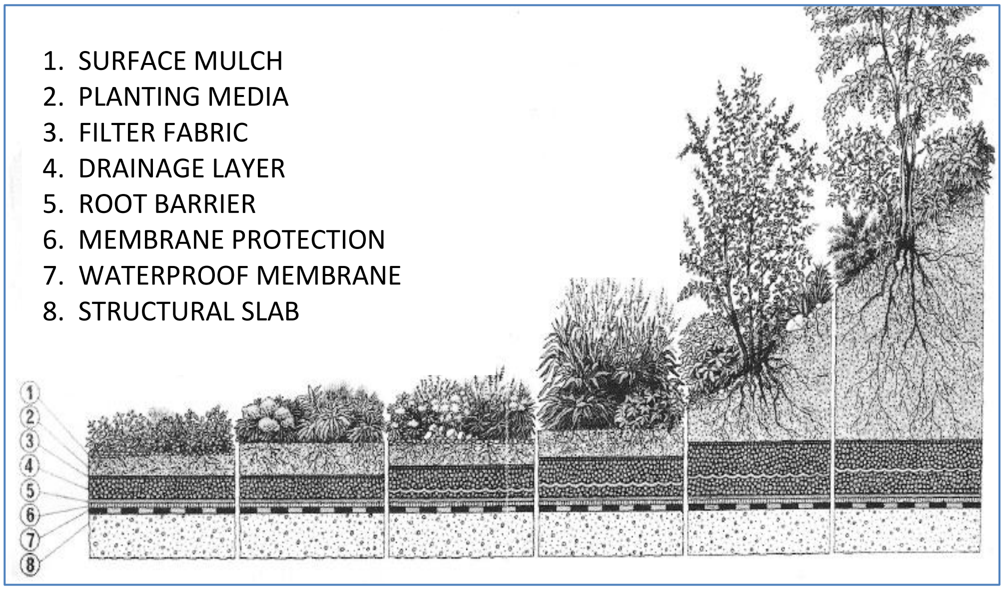


Figure 11. Variation of GR technologies; extensive (L) and intensive (R); (by Optima, via Osmundson, 2001).

Options for GR plantings are associated with variations in planting media depth, as well as slope, maintenance, and watering constraints. They include "extensive," "intensive," and hybrids of these applications, as shown in Figure 11, which provides a simplified and collective view of GR elements.

Table 1 delineates key differences between the three basic types of GR options detailed in Figure 11. Variations relate to how plants and other GR materials are applied to completed roofing membranes, and include an infinite variety of veneer and modular tile choices. Many of the intensive options require weekly to monthly maintenance to retain existing layouts or, more commonly, to keep weed growth in check. In most cases, irrigation is considered mandatory. Maximum-function GR installations typically entail automated irrigation systems 24–52 maintenance events per year via contracted maintenance. What Figure 11 does not show is how irrigation is included in the layout and maintenance of a GR.

Table 1.
Differences Between Green Roof Options (adapted with permission, Breuning, 2015)

GR Type	Extensive	Hybrid	Intensive
Substrate Depth	3–5 inches (76.2–127 mm)	5–7 inches (127–177.8 mm)	> 7–24 inches (177.8–609.2mm+)
Maximum Weight	15–25 lbs/ft²	25–40 lbs/ft²	35 to >80 lbs/ft²
Plants Used	Low-growing; sun and seasonally drought-tolerant or mesic; non-woody perennials, mosses and sedges (wet), herbs, sedums and succulents (dry) and rhizomous or stoloniferous grasses	Same as extensive, plus low to medium height (wind tolerant); perennials, sedums, ornamental bunch grasses, herbs, and shrubs	Same as hybrid; all heights of plants (some, or all in containers) including lawns, putting greens, shrubs, trees, and rooftop farming
Irrigated? * System Type	Not always; *depends upon local climate	As needed, hose or automated systems	Regularly, via automatic spray and drip systems
Maintenance Requirements	Low (1-2x/year)	Moderate(1-2x/month)	High (1-4x/week)
Relative Cost[1, 2]	Low ($5–$10/ft²)	Medium ($8–$25/ft²)	High ($20–$60+/ft²)
Potential Uses**	Passive: aesthetics, wildlife habitat (**all uses listed here also apply to Hybrid and Intensive roof options)	Limited to passive viewing + HVAC maintenance access; "living machines" systems can be located/used here	Food production, parks; active use by building patrons

(1) Standardization and certification of green roof products and the introduction of complete green roof systems may help minimize material costs. Specialization and training may also reduce installation costs (Philippi, 2006)."

(2) Guidance toward effective minimization of maintenance costs borne by GR owners and by asset managers (for use when buildings with GRs are for sale or in need of site management) is available on a piecemeal basis, and is dependent upon consumer familiarity with short- and long-term GR maintenance requirements.

Green Roof Component Choices

Numerous adaptable components and component combinations are now available. "Tray" modules, for example, can be prepared in situ, or ahead of installation. Both tray and layered veneer installations have trade-offs related to ease of installation, and to removal for the sake of membrane repairs. Site manager preference for tray-form GR systems is often based on the idea that access to the roof membrane is easier than that of a veneer system (personal communications, Crumrine, September 19, 2016; Evergreen State College Maintenance Staff communications, November 21, 2016). Although tile installations do provide easier access to membrane repairs, however, does not mean that leaks or other membrane issues to be repaired will be located where the tiles or veneer are removed. Use of proprietary electronic leak detection helps to pinpoint this serious failure issue, sometimes, without disturbing the GR (Miller, n.d.;. "Roof Leaks: Pinpointing and Repairing," 2010).

Both installation types, but especially tray systems, allow mixing of components (Cantor, 2008; Gill, Handley, Ennos, & Pauliet, 2006). However, component mixing from more than one product provider undermines the ability of owners to obtain warranties and, periodically, may also limit the availability of structural insurance (Shepard, 2010). Similar constraints also affect all levels of GR consultancies (Stern, 2009). Warranties are otherwise typically limited to periods ranging from six months to three years

Green Roof Planting Media Options

As a foundation for plant growth, GRs may be designed with infinite combinations of soil-like media. Balancing the weight of water-holding GR media without compromising the necessary details for thriving plant growth (when a GR is functioning at its best) is considered by many a proprietary art (personal communications, J. Breuning, October 2, 2016). Locally defined GR planting media biomes should be developed by qualified professionals to obtain the right configurations of soil-like planting layers and media with low release of fertility or harmful metals. Academics are also researching inoculation of GR media with soil organisms that aid retention and delivery of water and nutrients to GR plants expected to perform in less than hospitable primary succession rooftop habitats (Mandel, 2017; McGuire et al., 2013).

Jörg Breuning, a 36-year veteran of international GR installations and failure corrections, noted the precautions required to keep planting media free of weed seeds. Weed infestations are regularly associated with GR failure, either because the unanticipated plants overwhelm the intended GR management plan, the specified plantings, and/or because the weed extracts large quantities of rooting media when manually removed. Unless "weed-free" media is pre-specified, it can arrive at a construction site already infested. The stockpile must also be protected from pre-installation weed seed infestation (personal communications, J. Breuning, October 2, 2016).

Potential Green Roof Benefits

If a GR is properly designed, installed, maintained, and functioning as intended, a variety of public and private benefits are potentially gained, as summarized in Table 2 (greyed "x"'s indicate partial or subjective benefit perception). While the topic deserves ongoing research, the broadest application of GR technologies toward numerous outcomes can offset and aid human adaptation to climate change (David Evans & Associates, 2008; Rowe, 2011). Ecosystem services such as stormwater abatement and minimization of UHI are considered "externalities" which owners and utility ratepayers finance, and from which they sometimes obtain benefits. "Public" benefits benefit the commons—the neighborhood surrounding a GR, if not the broader community, including the quality of downstream water bodies and regional air quality. In addition to these values, GR installations can benefit local economies, and are promoted by the industry to ameliorate environmental issues associated with development and the vast expanses of impermeable and heat-absorbing structures that come with it. The most commonly promoted public benefits noted include a GR's ability to mitigate UHI, and/or a GR's ability to absorb and abate substantial amounts of stormwater precipitation.

Table 2.
Summary of Public and Private Benefits Potentially Provided by GRs

Ecosystem and Other Services Provided by Green Roofs (sorted by relative priority; note some benefits conflict with others)	**Private Benefits**	**Public Benefits**
1. Energy Savings		x
o GR + insulation aid thermal shell in summer months (this could be a negative, however, in cold/wet winters) (Breuning, et al., 2013)	**x**	
o Enhanced operation of photovoltaic systems (Breuning, 2013)	**x**	
2. Aesthetics (subjective and objective issues involved w/ determination)		
o Personal satisfaction is very subjective as is definition of aesthetic	**x**	
o Development of a Google Earth presence (Cantor, 2008)	**x**	
3. Stormwater retention + reduction of CSO (combined sewer system overloads) (Gill et al., 2006) + related reduction of downstream water course scouring (Shepard, 2010; EPA, n.d.)		**x** **x**
4. Stormwater quality, enhancement or decline via:		
o Filtration or leaching of applied nutrients (Simmons, Gardiner, Windhager, & Tinsley, 2008; Yang, Yu, & Gong, 2008)	x	**x**
o Filter air pollutant (depends on media, age of roof and nutrient application rates (Simmons et al., 2008; Yang et al., 2008)	x	**x**
o Reduced strain on urban infrastructure (Berndtsson, et al., 2006; Simmons et al., 2008; Yang et al., 2008)	x	**x**
o Landslide minimization (Breuning, 2011; FM Global (aka Factory Mutual Insurance Co), 2011)	**x**	**x**
5. Moderation of urban heat island effect, including:		
o In-situ energy efficiency; utility and customer monetary savings via passive evaporative cooling (U. S. EPA, 2008)	**x**	**x**
o "Upstream" energy production reduction (Peng & Jim, 2015)	x	**x**
6. Air filtration (esp. intensive GRs) (Yang, et al., 2008; Peng & Jim, 2015)	x	**x**
7. CO_2 sequestration (w/in plants and living soil, esp. intensive GRs) (McGuire et al., 2013; Peng & Jim, 2015; GRTech 2015a)	x	**x**
8. Doubled lifespan of conventional roofs via GR coverage (Liptan, 2010)	x	x
9. Personal health (mental /general) **and worker productivity amenities**		
o 40-sec views benefits worker productivity (Lee, et al., 2015)	**x**	x
o Hospital recovery rates (Getter & Rowe, 2006)	**x**	x
o Crime reduction (Entrix, 2010)	**x**	x
o Japanese Shinrin-Yoku ("forest bathing") (Townsend & Weerasuriya, 2010;)	**x**	
10. Ameliorates habitat needs (Brenneisen, 2012; van Heezik, Dickinson, & Freeman, 2012)	x	**x**
11. Sound abatement (Peck, 2001)	**x**	
12. Urban food security, marketing, and jobs (Fischer, 2012; Wetli, 2016)	**x**	**x**
13. Applied water treatment systems ("living machines") (GRTech 2015a)	**x**	x
14. Trade-off involved with fire (Thompson & Sorvig, 2007; Philippi, 2005))	x	x
15. Camouflage (parking lots, cisterns, water treatment and reservoirs, bunkers, tunnels, aviation hangers, plus home and work spaces (var.)	**x**	**x**
16. Enhanced real estate values (Gamerman, 2014)		
o Higher rent values (esp. if GR is accessible) (Verrati, et al., 2005)	**x**	x
o Higher average property value overall	**x**	x
o If accessible, attractive to business and their customers	**x**	**x**
17. Education and job opportunities (Peck, et al., 1999; Mother Nature Network, 2012; Doshi & Peck, 2013; Dalzell (NRDC), 2016)	**x**	**x**
18. Aids accrual of LEEDs/other certification points (Eisenberg, Persram, & Spataro, 2009)	**x**	
19. Regional economic enhancements /Generate tax revenues (EPA, 2013; Peck, 2016)		**x**

Green Roof Constraints

Slope and Load. Depending upon desired outcomes, GR components can be installed on flat, as well as slightly to steeply sloped roofs, however, most are installed on roofs that are considered flat (Cantor, 2008; Gill, et al., 2006; Thompson & Sorvig, 2007). Static and dynamic loads are a critical factor that must be addressed by qualified architects and engineering professionals during each building's structural design, or enhanced in existing structures to accommodate the permanent and changing weights of GR elements and amenities.

Weight-loading components include waterproofing membranes and membrane protection fabrics and paths, plants, their growth and plant media, irrigation and drainage systems, the water that plants and media absorb over varied periods of time, the addition and movement of people and furnishings within the GR area, and, in freezing climates, the dead weight of ice and snow loads. Catastrophic GR failures have been caused by unanticipated snow load that thawed, refroze, and collected more moisture from poorly routed drainage and/or unheated GRs (Noriega, 2011; Breuning, 2011). Similarly catastrophic are incidents of failed GRs occurring during construction when the dead weight of GR products being delivered was accounted for or evenly distributed, resulting in complete roof cave-in and lives lost (Yurek, 2013).

Irrigation. Despite Portland's interest in unirrigated ER installations, a majority of this community's vegetated roofs are irrigated to enable a larger range of amenities. These mostly private benefits include a broader selection of plant species and enduring plant performance, even during non-drought periods (Sutton et al., 2012). Irrigation also enables plant and soil media evapotranspiration, the concept that facilitates thermal cooling of structures, and thus UHI remediation (MacIvor, Margolis, Perotto, & Drake, 2016). In certain regions like Portland, heat and drought already challenge survival of unirrigated GR plantings that were designed and established to endure normal summer drought. Because heat spells are predicted to increase in number, duration, and severity with climate change (Mauger et al., 2015), hotter and drier weather patterns will likely increase the demand for GR irrigation. Thus, irrigation highlights a potential benefit contradiction. Whether, or not, UHI amelioration via irrigation is a cost-effective response in the midst of limited water supplies will help to determine whether or not GR become a more regulated luxury.

Ecoroofs: A Baseline for Analysis of Green Roof Failure

The "ecoroof" (ER), as used in the marketing of GRs in Portland, Oregon, is a concept specifically created to promote both environmental and "eco-nomical" stormwater management objectives (Cantor, 2008; Liptan, 2016). Ecoroofs provide municipal utilities with externally managed ecosystem services for stormwater abatement and filtration (City of Portland [Asset Managers Group], 2008; Spolek, 2008; Entrix, 2010, p. 1.4.1, p. 2.2; Caballero, Kahn, & Prinz, 2016, pp. 2, 4, 6). Similar to the membrane lifespan of GRs (as per Mullen, 2015), private and public sector ERs are also expected to protect and outlast the 20- to 40-year duration of the conventional roofs on which they are installed.

Landscape architect Tom Liptan, the primary developer of Portland's GR incentive program, indicated that ecoroofs (ER) are privately designed and managed. It is his hope that an owner's intention will result in a GR that can survive without supplemental irrigation after the standard one to three years of establishment (and typical period of warranty coverage). In addition to his appreciation of naturally occurring moss or weed growth, Liptan suggests that ERs be designed to consist of drought-tolerant plants. These are usually a blend of sedum species or a mixture of grasses and forbes. Over time, intended low-maintenance ER plantings increase their function by evolving toward a healthy soil biome with a balance of original plants interspersed with invasive weeds, moss, or both (personal communications, T. Liptan, February

1, 2016, and January 19, 2017; C. Cunningham, August 23, 2016; Lundholm, MacIvor, MacDougall, & Ranalli, 2010). Whether or not ERs provide subjectively determined aesthetics is of less concern to Liptan than the resilience-related stormwater retention and water filtration that ERs can provide (T. Liptan, January 19, 2017).

Inclusion of sites with naturally occurring moss and “weed” growth among GRs on the COP/BES list of sites signifies this kind of ER provides stormwater benefits. None of the “natural” GRs on the COP list was the recipient of an incentive, and other than the list, none receive specific marketing. Modest and passively managed ecoroofs are achieved without adding traditional horticultural resources, and they clearly self-sustain as well and sometimes better than professionally installed GRs (personal communications, T. Liptan, January 25, 2017). Mixed-species ERs are also promoted in Portland as offering habitat attractive to birds, insects, and wild plants, all of which have lost ground to encroaching development (Cunningham & Liebezeit, 2015). For simplicity, this thesis will include ERs as a form of GR unless a comparison is needed or specifically identified. As a representative agency, Portland’s interest in other benefits generally associated with GRs (see Chapter 4, Parts I and II) is comparatively limited.

Foundations for GR Failure Analysis

This section of the thesis establishes terminologies for the sake of thesis research and comparative analysis. Categories of GR failure are considered along with the representative professional interests engaging in GR promotion or installation.

Defining Green Roof Failure Categories

Creation of an operational definition of GR failure is first built upon a separation of failure into hypothetical “non-failure,” “partial failure,” “total failure,” and “catastrophic failure” categories, as noted in Chapter 1, and defined as follows.

Non-failure. Non-failures are hypothetically defined as transitory or long-term GR issues that affect either the psychological and/or financial appreciation of the GR by the owner or respectively, in the case of a bank-owned asset, an inability to market a vacant building because of the GR that has been installed upon it. Examples of "non-failure" issues associated with GR includes failure to fulfill non-functional objectives such as return on investment (ROI), access to insurance, or mortgage lending. Aesthetics also qualify as "non-failure" and are similarly not related to GR function, but related instead to owner intention. Aesthetic failures are purely subjective, and generally involve an owner's disagreement with seasonal or long-term visual outcomes of their GR installation. Resolution of "non-failures" can sometimes result in GR removal (equivalent to "total failure").

Partial failure. Partial failures are hypothetically defined as transitory GR issues that can be repaired without needing to remove the GR, or when whatever warranty may have been purchased by the owner covers repairs that do require temporary removal of the GR.
Partial failures also include more difficult-to-resolve access, maintenance, and planting issues, as well as more subjective issues related to costs and aesthetics that are egregiously different than what was originally promoted, specified, or contracted by the provider(s) to the owner. Partial failures may overlap with non-failures from an owner perspective when the non-failure becomes a failure that affects the owner, such as difficult GR access or overwhelming plant growth and other horticultural issues. Partial failures tend not to result in GR removal.

Total failure. Total GR failures are hypothetically defined as long-term, entrenched issues that consistently trend toward GR removal and/or involve major GR or roofing membrane repairs. Examples of total failures include leaks that require removal of the GR to locate and repair, drainage issues that are similarly resolved with GR removal, significant and/or repeated plant or media failures, repeated or accumulated partial failures, or other issues that snowball into temporary or permanent GR removal. Cost overruns, especially those that result in litigation which collectively exceed 50 percent of the value of the GR, also qualify.

Catastrophic failure. Catastrophic GR failures are hypothetically defined as issues limited to structural collapse (regardless of the cause) requiring repair or reconstruction of either the GR and/or the structure on which it was installed. Despite potential GR benefits to be gained, the experience or perceived risk of such failures can result in a consumer's permanent reconsideration of GRs as a roofing option.

Green Roof Experts and Their Interests

The organization of GR experts into interest-related categories highlights and enables numeric analysis of survey results from all groups, which provided a range of perspectives about issues associated with GR failure. Specifically, these interest groups include: 1) representatives of agencies providing GR incentives; 2) representatives of the GR industry; and 3) GR customers. Differences also occur within these categories; for example, industry representatives may include different stakeholders such as practitioners, manufacturers, and product providers. Another group, GR educators, was disaggregated for specific analyses that follows because the issues cited by them were substantially different from all other groups. Their unique perspectives became evident after the first survey analysis was close to completion.

Expert GR interest groups are defined and each groups' objectives are identified in the following list.

Agencies providing green roof incentives. Stormwater management, UHI amelioration, and/or energy savings are the primary objectives sought by agencies providing GR incentives. Some agencies (and ecologists) additionally encourage colonization of insects, birds, bats, and other wild species that provide pollination and pest control services, along with locally marginalized endemic native plants. Public use of private GRs for carbon sequestration may eventually become an important GR outcome sought by public agencies.

Green roof industry representatives. Individuals in this category include engineers, architects, landscape architects, GR product manufacturers and providers, and GR contractors. Beyond marketing products and services, the primary objective of GR industry representatives is creation and fulfillment of owner, and/or planner-derived GR intentions. GR objectives established in the agency category above may also influence those of the industry.

Green roof customers. GR customers are willing to pay for private GR benefits and amenities, such as aesthetics and warranties that cover avoided future costs. They are not, however, consistently interested in the objectives listed for agencies and GR industry representatives. Representative owners participating in the expert survey defining GR failure included individuals overseeing the design, construction and long-term management of large, public-owned GRs.

Green roof educators. Educators, for the sake of the thesis, include industry technician and specialist educators who train GR professionals, and secondary academic educators providing GR-specific programs at established colleges and universities. Failure criteria identified by educators tends to focus on product performance, social and economic aspects of GR installations and/or on the measure of environmental benefits potentially provided by GRs.

Educators were left out of initial interest categories, not because they don't matter (they do), but because differences reflected in their concerns were not evident until after primary survey data was analyzed. The results, discussed in Part II of the thesis, compelled the author to add educators as a separate representative category in the data analysis because their correlations of issues with GR failure show priorities that differ from other interests.

Chapter Summary

Establishment of failure categories supports post-thesis communication regarding GR failure. It also provides a measured basis by which GR failure can begin to be consistently framed and measured. Likewise, an understanding the different interest groups involved with GRs not only allows for increased understanding of different perspectives that are held by each, but also establishes the foundation of a market analysis.

Chapter 3 - Literature Review

Having described GR components and defined levels of failure among interests that comprise the marketplace, the next concern is identification of market features that resemble failure. The literature review provides examples by which utility agencies, GR owners, educators, and the GR industry can employ failure analysis to individual and collective benefit. Chapter 3 first addresses the lack of failure literature specific to GRs and then bridges it with alternative approaches. Examples of other industries that do utilize failure analysis provides a basis for development of operational failure criteria for use by the GR industry. Aspects of GR failure analysis ultimately do exist–they simply haven't been assembled into a useful whole. This section of the thesis examines the puzzle pieces and organizes them to reinforce surveys that develop industry-derived definitions of GR failure in Chapter 4.

Absence of Green Roof Failure Resources

Current GR literature (academic and otherwise) has become prevalent since 1970, with non-English guidelines originally published in Germany (FLL/Forschungsgesellschaft Landschaftsentwicklung Landschaftsbau (a.k.a. the German Landscape Development and Landscape Research Society), 2008). A literature review regarding thesis topics, however, reveals a gap of *academically* published failure rates for GRs, including a lack of operational definitions of GR failure. These voids are evident throughout global GR industry promotions and literature from all North American state and federal agencies enacting policy favorable to GR installations or otherwise encouraging green infrastructure that includes GRs.

Academic literature relating to GRs, generally, provides information tangential to GR failure. To overcome the limitation, sources considered for this thesis (i.e., Cantor, 2008; Getter & Rowe, 2006; Gill et al., 2007…) are numerous, varied, and provide a synthesis of GR research and educational guidelines for consumers, utility agency representatives and GR industry participants. Non-academic resources, including industry marketing materials, media reports both for and against GRs, and personal communications with GR owners, managers, and GR program representatives complete the list of resources utilized.

The Landscape Architecture Foundation's recent posting of *The Landscape Performance Series*, a revision of its prior *Case Studies Investigation*, starts to address failure reporting through documentation of "environmental, social, and economic benefits…" of landscape and GrIS projects, which includes GRs among numerous projects (Landscape Architecture Foundation, 2016, p. 2). Data are only recently being populated in this system, however, and do not yet include failure-specific details or related insights.

Failure Analysis by Other Industries

Countless perspectives on failure analysis exist, and still more on industry process and improvement are built upon foundations of acknowledged failure. Aerospace, automotive, construction, and health care professions benefit from the failure analysis process, as do interests in computer and industrial engineering (Aliya, 2002; Otegui, 2014; Pusey, 1996; Vaidya & Kumar, 2006), business management (Edsel, 2016; Nelson, 2016), ecological economics (Costanza et al., 2016), and ecological sustainability (Costanza, 2007; Mayer, 2008).

The GR industry, within the context of the larger world of GrIS and the even larger context of utility infrastructure, is relatively young, especially in North America. Now that two decades of incentivized GR installations have accrued in North America, the impetus exists to evaluate what has been accomplished. Observing how other industries approach failure can provide thesis shortcuts and best practices for the application, rather than reinvention of failure analysis that invites significant progress toward the broadest range of GR benefits among all interests, but especially stormwater management and urban resilience among utility agencies, with potential application to other GrIS systems.

The following approaches provide a simplistic overview of options available, which include Fishbone diagramming, Fault Tree Analysis, Failure Mode and Effects Analysis, Reliability- Based Analysis, and “The Outside View.” Each approach offers different levels of failure analysis complexity to either individual GR owners and managers, and/or to a collective view of GR assets by utility program managers respectively seeking to protect their incentivized installations from potential failure issues or to discern existing but not fully understood problems.

Fishbone diagramming of failures. Known as “Ishikawa diagrams,” or “cause and effect diagrams,” “fishbone diagrams” consider single and multiple project failure issues within the least complex framework of a systematic and graphic format, as illustrated in Figure12.

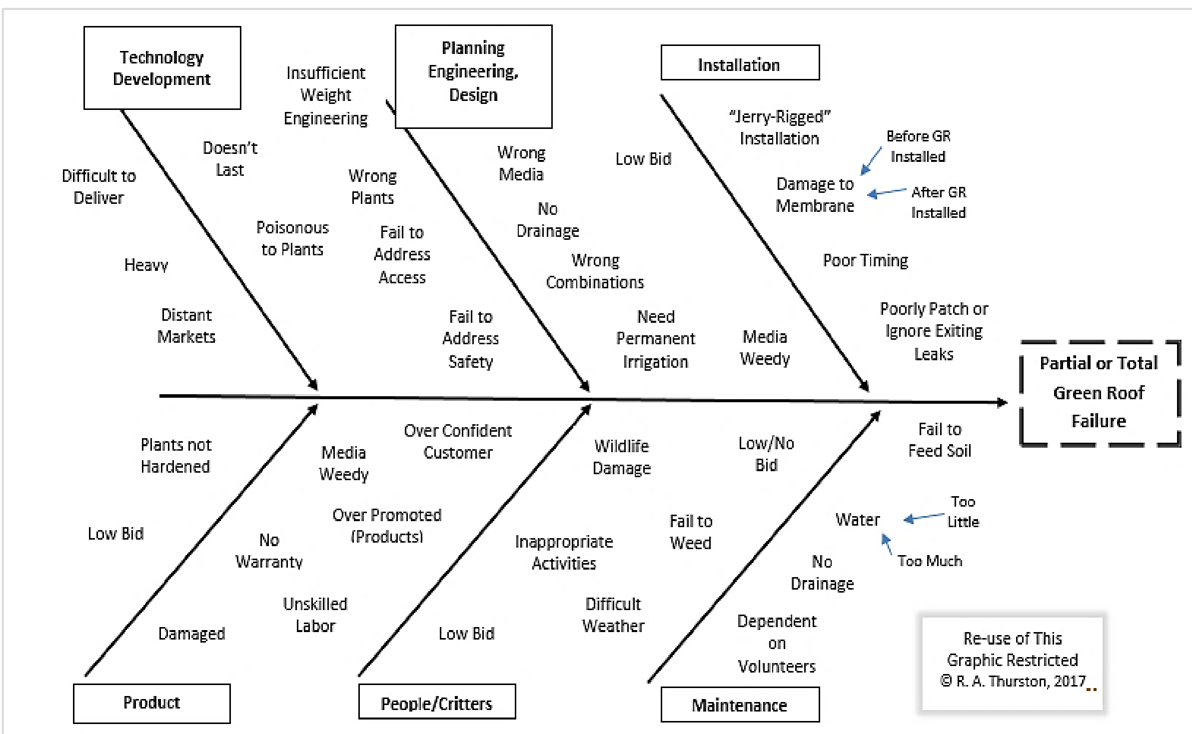


Figure 12. Cause and effect in green roofs. (©RAThurston)

Fishbone diagrams support “root cause” or Fault Tree Analysis (FTA, to be discussed below) by providing lists of subordinate and increasingly categorized project aspects that ask why a known problem exists. Unlike the FTA approach, which limits results by branching out and by weighting known subordinate failures, the fishbone gathers basic information toward a single failure outcome, which resembles a fish skeleton. This simple approach is visually informative and compelling because it accommodates multiple layers of varied quality input and requires little explanation to understand the sequence of individual and/or accumulating issues that contribute to a particular failure. Fishbones, as applied to GR failure, could be useful to communication of risk assessment, and for prevention planning of avoidable GR failures.

Fault Tree Analysis (FTA). The FTA approach is an easy to implement "top-down" system that graphically resembles tree roots. The FTA process is most useful if the causes of failure are not fully evident, but the failure outcomes are, especially in individual GR failure analysis. FTA uses a true-false Boolean process that allows users to understand and detect already evident failures. Categorized failure evidence provides starting data, with each outcome followed by layers of "yes" or "no" answers to questions that eventually lead to specific failure contributors. Free templates are accessible online and are also embedded in popular software programs for many applications. The next logical step in the analysis is adding weighted values to each issue to allow calculation of severity and/or risk, as provided by the FMEA approach that follows.

Failure Mode and Effects Analysis (FMEA). The "bottom-up" approach of FMEA was among the first failure analysis techniques developed at the turn of the 21st century. The system allows a calculated and weighted likelihood of failure occurrence by type and severity. By cataloging system components and functions during the design phase, one can consider the loss of components and/or function of necessary features (or both, if a project is complex). The FMEA process overcomes numerical limitations presented by processes that do not incorporate subordinate issue weighting and cost calculations

Table 3.
Sample Failure Mode and Effects Analysis Using Green Roof Data Inputs (modified, using teaching example provided by Glancey, 2006)

Item	Component or Function Identification	Description	Failure Modes	Effects	Safeguards	Prevention, Detection and Repair Actions	Probabilities and Value(s) of Failure
1	**GR Drain System** (both a piece of hardware, and a functional aspect of any GR)	• Accepts precipitation when GR media is saturated • Allows moisture to drain via gravity	• Clogs: • Ice, media, debris, other • Water backs up • System can't filter • Plantings inundated • Media eroded	• Media floats • Plants drown/die • Pooled water penetrates flashing/alt… • Structure Leaks • Structure failure under dead weight • GR overflows beyond drain or gutter • Downstream water quality issues	• Team communication • System engineering accommodates media and site constraints • Quality products • Qualified plan review • Installation oversight • Record-keeping • Planned failure response • Warranty	• Bi-monthly overall GR inspection • Drainage test on __x/yr. basis • System evacuation on __x/yr. basis • Team review of failures	• Likelihood of failure to occur (as a % unit) • Cost of system installation • Cost of regular maintenance • Cost of drainage test • Cost of system evacuation • Cost of failure penalties • Failure related costs
2	Structural Membrane	• Protects structure from external environment	• Leaks • Ages prematurely • Becomes detached from structure…	Etc.…	Etc.…	Etc.…	Etc.…

Once component features or processes are added as separate categories in a standard spreadsheet, details regarding failure modes and effects are added to each category. Related probability of occurrence and of detection are then added and a numerical severity rating value is assigned and calculated at every level.

Specific to the GR industry, a FMEA spreadsheet might initially look like the two-tiered example provided in Table 3. For any comparative failure analysis, weighted values need to be non-subjective, and numerically based to facilitate replicable cost calculations associated with GR features. A thorough analysis would include individual columns that address specific failure causes, plus additional columns where weighted (mathematical) ratings would be inserted for automated calculations by the spreadsheet application.

Boeing engineer D.P. Dennies is cited by Aliya in an undated treatise, as having used the FMEA approach by way of the nine steps outlined in Table 4. The word "objective" stands out as an operative requirement in the items listed. Self-assessment and continuous objectivity may be a task best facilitated by an unbiased third party.

Table 4.
Nine-Step Failure Investigation (as per D.P. Dennies, quoted by Aliya, 2010)

1. Understand and negotiate goals of the investigation.
2. Obtain a clear understanding of the failure.
3. Objectively and clearly identify all possible root causes.
4. Objectively evaluate likelihood of each root cause.
5. Converge on the most likely root cause(s).
6. Objectively and clearly identify all possible corrective actions.
7. Objectively evaluate each corrective action.
8. Select optimal corrective action(s).
9. Evaluate effectiveness of selected corrective action(s).

It is possible that individual members of the GR industry already use FMEA as a failure analysis tool because it adapts to failures discovered post-installation. If not, development of standardized FMEA cost data sheets could provide needed communication between owners, GR managers, asset managers, and agencies responsible for financial and asset reporting. Complex GR installations, especially those that mix components from different suppliers, or which use new or non-traditional products could possibly challenge this failure assessment approach, however. To the degree that the process is not standardized, variations produced by proprietary applications would result in varied outcomes that leaves regulators without comparable data.

Reliability- Based Analysis (RBA). Sharing many of the features of the FMEA approach and closest to the GR industry is "reliability-based analysis" applied to the roofing industry to predict roof service life (Kyle & Kalinger, 1999). Kyle and Kalinger's 1999 statistical databases, and probability theory addresses "limit states" of roofs and roofing components to measure "performance requirements, inspection, preventative maintenance, repair, and major rehabilitation decisions" that influence financial choices throughout the life of a roof, and/or roofing components. The system is elemental to life-cycle cost analysis (LCCA) and provides discrete calculation of sub-category details to accommodate the mushrooming array of project and product diversity in new roofing materials, configurations, and assembly options.

RBA accommodates multiple variables, including the random nature of roofing service loads, as well as design and maintenance. Although it is complex in its use of Monte Carlo probability formulae, the approach could be useful to detailed analyses of GR performance, especially for litigation involving significant distribution of funds and determining liability among multiple parties.

RBA is, however, dependent upon maintenance of asset management records capturing design and inspection data. Use of inconsistently dated “snapshot,” data makes application of the analysis process difficult – a limitation that would detract from its application to GRs with the data that is currently available.

The outside view. Considering GR failure from an external, program-wide, high altitude perspective, provides a different approach to the subject if GR failure. Flyvbjerg pursues failure analysis from a perspective of project management quality control that relies upon data benchmarks (Flyvbjerg, 2013). The “outside view” analysis process confronts cost overruns, candidly stating that “front-end estimates of costs and benefits -- used in the business cases, cost-benefit analyses, and social and environmental impact assessments that typically support decisions on projects -- are typically significantly different from actual ex post costs and benefits, and are therefore poor predictors of the actual value and viability of projects” (Flyvbjerg, 2013).

The “outside view” specifically addresses infrastructure and highlights government stimuli made available to public agencies in countries around the world during the global recession that started in 2008 (Flyvbjerg, 2009). Characteristics of major infrastructure described by Flyvbjerg include references to project risk, adoption of non-standard technologies, dependence upon community-designed and -built systems, expected evolution of projects and related community ambitions, the likelihood of unplanned events and related cost overruns, and related misinformation that sometimes results from all of these details. The due diligence that Flyvbjerg recommends involves eight steps, as listed in Table 5, that address the cost-benefit process commonly employed among the GR and GrIS trades and by their agency allies, who further fund the incentives on which GRs remain dependent (as first reported by Peck, 2001; and reiterated, Peck, 2016(b)).

Table 5.
Eight-Step Due Diligence for Program Cost-Benefit Analyses (as per Flyvbjerg, 2013)

1. Identifying and describing the business case or forecast to be developed.
2. Establishing a benchmark that represents the outside view, against which performance may be measured.
3. Using the benchmark to evaluate performance in the forecast in question.
4. Checking the forecaster's track record from other, similar forecasts.
5. Identifying further cost and benefits risks.
6. Establishing the expected outcome.
7. Soliciting comments from the forecaster.
8. Concluding as to whether the forecast is over- or underestimated and by how much.

The point of referencing these resources is to demonstrate how failure analysis can benefit the development of GR asset management and related enhancement of infrastructure resilience. The resources can also be applied to all aspects of the design, implementation, and maintenance of sustainable infrastructure assets similar to GRs. The GR trade would similarly benefit by way of an increasing count of GR installations experiencing greater longevity. Regardless of the approach used, the organization of one's investigation needs to be replicable, as well as readable by others (Aliya, 2010). Relative to the question of GR failure underlying this thesis, adoption of a single standard would facilitate the most effective development of the GR trade.

Other Names for Green Roof Failure

Non-academic information providing terminology closest to a definition of GR failure includes infrequently peer-reviewed or scientifically tested trade resources and reflects provider marketing bias. This material includes web blogs and articles posted in GR industry magazines (many of which are managed by Green Roofs for Healthy Cities or the affiliated Landscape

Architecture Foundation), as well as consultant and product provider websites. Little of this information mentions "failure" outright (Building.Co.UK, 2008).

GR trade and academic articles reference "disadvantages" related to GRs (McGuire et al., 2013; Salter, n.d.); as well as numerous analyses of "barriers" to GR installation (Eisenberg et al., 2009; Fünfgeld, 2010; Getter & Rowe, 2006; Hendricks & Calkins, 2006; Jacobsen, 2009; Liptan, 2010; Oberndorfer et al., 2007; PSU, 2005; Seattle DPD, 2016). "Challenges" are another frame under which the currently limited application of GR failure is considered (Henry & Frascaria-Lacoste, 2012; Ulam, 2016). Other terminology regarding this topic includes "concern" (Cantor, 2008); and "worry" (Chotiner, 2014). Only articles highlighting specific GR project failures were found that address GR failure as an issue unto itself. Within the analysis of individual GR failures, design-deficiency and safety issues register frequently among GR managers and inspectors (Morby, 2015; Spadafora et al. (FDNY), 2009).

"(Dis)incentives" (Miller et al., n.d.) are also considered, as are "property loss prevention" resources which look at insurance aspects of GR installations (FM Global (a.k.a. Factory Mutual Insurance Co), 2011). "Worst case scenario" and "lessons learned" topics examine failure costs (Breuning, 2009; Carter & Keeler, 2008) and the dusproven perception of GR fire hazards (Breuning, 2008). Lastly, industry "needs" are considered from a variety of facets, including policy (Carter & Fowler, 2008; Jacobsen, 2009); research (Franconi, 2012; GSA, 2011; Magill, et al., 2011); and evolving green infrastructure trends (Cassidy, 2016; Whiteford Taylor Preston, 2016).

Non-academic GR trade resources that do examine failure can be disparaging of North America's GR products, engineering, and professionals installing and maintaining GRs. It makes sense, however, that the North American market may remain in a perpetual state of catch-up with European GR markets after having only two decades to establish a scaled-up industry in a much larger geographic area with varied product outlets and resources. In addition, the European market that exemplifies GR trends generally operates under economic systems that value natural capital more than has been pursued in North America (personal communications J. Breuning, December 18, 2016). Resources highlighted are otherwise incrementally beneficial to a holistic understanding of evolving trends, products, practices, and consumer demands amid a rapidly changing North American, and global GR marketplace.

Conventional Roofing Lifespans and Failures

Roofing engineer Carl G. Cash came the closest to defining GR failures in his 2003 publication *Roofing Failures* (Cash, 2003). This text and a government contract publication (Cash & Bailey, 1993) address conventional roofing systems and green roofs as a sub-market niche. Conventional roof lifespans provide a comparison to differentiate between roofing failures and GR failures. The text by Carl Cash provides an accounting of failure types, but not necessarily the rates of failure (Cash, 2003). His later reports, however, do provide useful details (Cash & Gumpertz, 2005) as does the GAF-published booklet *Roofing Solutions*, which illustrates "How roof maintenance saves valuable dollars" (Russo et al., 2006). However, this resource doesn't summarize the "average" roof's lifespan.

Complicating the question are detailed analyses of numerous types of conventional roofing membrane applications against a broad variety of situations and factors that affect each roofing product's duration. Sought-after roofing failure rates were first found in the older publication co-authored by Cash (Cash & Bailey, 1993), but considered unreliable because so many of the details within the trade have changed. A slightly more current analysis not only examines the multiple variables, but mentions an aggregated average conventional roof lifespan of 20 years (Kyle & Kalinger, 1999).

Difficult, but potentially important to measure, is whether GRs outlive the lifespan of the membrane on which they are installed. The marketing promise that GRs will protect roofing membranes is common and suggests that GRs will not only protect the membrane, but will potentially double its lifespan (or better), thus adding longevity and integrity to the structural roof. The GR industry has, however, not been in place long enough to truly test the lifespan assertion. The concept makes sense, but there are a number of caveats that undermine the simplified promotional argument. Among them is an, often, unstated expectation of GR maintenance, a catchall requirement assumed to be known among consumers. The maintenance expectation encompasses many activities such as weeding, appropriate drainage maintenance, irrigation, etc. all of which is built, literally, upon the assumption that the membrane has been effectively designed, protected, and installed before the GR is applied.

Issues Enabling Green Roof Failure

A variety of issues make GR failure more likely to occur. The tangential analysis of particular issues that enable GR failure, however, is much broader than the thesis allows. Superficial references included here are as much a reality check for would-be GR consumers as a call to members of the trade to meet the demand for horticulturally-skilled consultants. The things that attract customers to GRs may otherwise be the over-simplified issues that encourage them to fail, and/or to discontinue their part in the GR trend at a later date.

Understanding Green Roof Horticulture

In the primary succession environments of GRs, horticulture dynamics are metaphorically like the colored squares of a Rubik's Cube puzzle (see https://www.rubiks.com/). Where misalignment occurs among necessary elements of a GR's biotic features, so too will failure—subtle or extreme, short-term or eventual—likely be evident. Horticultural issues can be addressed singularly, but an understanding of horticulture as a holistic system enables prevention of failure issues that often occur in tandem with one another, and/or as a result of minimal design. Avoidance of GR failure requires management decisions to be based on sound horticultural knowledge and/or experience that cannot be fully understood from a quick reading, or postponed when one is over-committed.

The focus of North American GR resources addressing horticultural systems tend toward promotion and use of nationally-marketed plants (Dunnett & Kingsbury, 2004; Novak, 2016; Snodgrass & Snodgrass, 2006). Popular consumer literature otherwise tends to address GR benefits and/or the mechanics of GR design and construction (Osmundson, 2001; Snodgrass & McIntyre, 2010; Thompson & Sorvig, 2007; Weiler & Scholz-Barth, 2009). Peer-reviewed literature is only somewhat helpful to consumers because of its technical or academic orientation and consideration of singular and/or scientific topics (e.g., Oberndorfer, et al., 2007, among numerous others). Technical and non-technical GR resources that addresses *localized* horticulture dynamics is even more limited, but important because all eco-regions have their own seasonal and geographic variations that further affect the outcome of GR installations.

Willingness to Pay for Failure Prevention

Reliable maintenance often involves hands-on labor from individuals who are also horticulturally knowledgeable. These individuals may also need to be capable of managing irrigation systems for both plant health and water conservation on at least a monthly basis (more often than that at the outset of the GR installation to verify irrigation and plantings are working as intended). In the face of GR contract maintenance costs ranging between $1/sf and $3/sf per contract period (personal communications, J. Breuning, January 5, 2017) and given a typical minimum of one to three years before GR establishment some owners are tempted to provide GR maintenance themselves. Communications with multiple GR owners supports this finding, regardless of whether the owner is familiar with what's involved in terms of time, physical labor, and/or horticultural expertise (personal communications, L. Ariston, 8/15/16; J, Miller, 08/24/16; K. Unkeles, 8/29/16). GR care may be alternately delegated to staff who already handle other building maintenance issues but who may also have little or no horticultural expertise (as per survey findings among GR owners). One-, three-, or five-year GR maintenance packages can be purchased instead of more costly warranty coverage for plantings, but are generally not inclusive of the membrane (personal communications, J. Crumrine, January 3, 2017).

Warranties that address membrane lifespan are sometimes used as an alternative to maintenance plans, but rarely offered for more than three-years (personal communications, J. Crumrine, March 2, 2017). Warranties also add significant costs to the installation of the GR (personal communications, J. Breuning, February 20, 2017; J. Crumrine, March 2, 2017). Given the similarly significant cost potential associated with structural leaks, regardless of whether or not leak(s) originate with the roof, the GR or its installation and management, it seems prudent for owners to address these concerns but they need reliable failure data with which to do so.

Leaks: Before, During, or After GR Installation?

Industry resources state that leaks are among the three leading failure issues associated with GRs (Haisley, 2001; Sibelius, 2009; University of Applied Sciences, Wädenswil, 2005). Justin Henshell, FAIA,CSI, FASTM, synthesizes the issue while demonstrating latent inter-industry priorities, stating, “Despite the emphasis on ecological benefits, experience tells us that nothing will discourage the enthusiasm for green roofs as much as a leak in the boardroom below” (Henshell, 2005a, p. 27). Henshell illustrates the potential for misplacing the blame for leaks on GRs when he states as a generalization that “…many proponents [of green roofs] have ignored or dismissed the importance of the underlying waterproofing membrane upon which the success or failure of the green roof assembly depends” (Henshell, 2005a p. 27). Leaks were recognized in a similar light in a presentation to the World Green Roof Congress in Basel, Switzerland by Wolfgang Ansel, in 2005.

Roof vs. Green Roof Cause Debate

Given the multiple public and private benefits potentially provided by vegetated roofs, there is much to gain from GR installation (see list of benefits provided in Chapter 2). However, GRs are not nearly as simple to design and install, nor as labor-free, as conventional roofing alternatives (Maddox, 2015). Complicating these issues is a lack of consumer and owner differentiation between the roof and the GR, since these items are not just adjacent to one another but can be designed to be integral to one another.

Industry articles from different sectors of the GR trade (i.e., roofing industry, landscape architecture, horticulture, and GR specialists) have debated the cause of these issues, sometimes blaming other sectors of the trade for leaky membranes (Sibelius, 2009). Portland GR consultant Jon Crumrine seeks to minimize the misplacement of blame upon GRs or the tradespeople who install them by carefully distinguishing between roof membrane issues and GR issues. According to Crumrine and industry BMPs (Sibelius, 2009), verbal references and contractual semantics are important to differentiate GRs as separate from the membranes on which they are installed to minimize the confusion and misplaced blame this issue creates among consumers and between different aspects of the GR industry (i.e., large-scale roofing companies and small-scale GR consultants).

Part of the problem may be due to a lack of membrane protection prior to GR installation, an issue that can occur well before the GR consultant participates with the project (personal communications, The Evergreen State College maintenance staff, February 9, 2016). Without insight into such issues, the GR consultant has minimal ability to disprove fault that might have been better placed upon any number of individual or combined issues. These include: normal wear and tear of existing membranes; non-installation or improper use of non-specified or inadequate alternate drainage components, membrane, and/or flashing products; and/or use of the area where the GR is eventually installed as an unprotected pathway.

In addition to site-specific, exact, and thorough contract documents and specifications, current best practices include pursuit of one to two membrane leak detection tests from a choice of technologies prior to GR installation. Since 2010, Toronto, Ontario, which requires that GRs cover 20% to 60% of the roof on “all buildings with a gross floor area of 2,000 square meters or greater” exemplifies the leak detection options available in its municipal code (Green Roof Technical Advisory Group, 2013, p. 492-6). These include: electric field vector mapping, impedance tests, infrared thermal imaging, low- and high-voltage testing, and the use of moisture sensors (Green Roof Technical Advisory Group, 2013).

However, many of the above references and comments consider failures occurring prior to the development of leak detection technologies. In the past, leak detection was limited to visual inspection and short-term flooding to see if water appeared below the roofing membrane (i.e., causing damage to avoid it). Henshell’s dismissal of GR proponents seeking ecological benefits muddies the fact that membranes in and of themselves fail. Now that the GR industry has developed both its product and installation approaches, the cause of membrane leaks is considered to be less attributable to the GR installed above it (personal communication, J. Crumrine, January 3, 2017).

Beyond the risky pursuit of membrane flood-testing prior to GR installation, there are a handful of technologies available for leak detection, a few of which can be applied after the GR has been installed, supposedly, with minimal to no disruption of the GR required to locate the leaks. Once roof membranes start leaking, however, some structures become permanently compromised, leading to significant costs and a reluctance among maintenance staff to reinstall

GRs (Russo et al., 2006; personal communications, The Evergreen State College maintenance staff, February 9, 2016). When leaks do occur, accessing the leaky roofing membranes covered by the overburden of GR product is not just difficult, but expensive. Moreover, the effort does not always yield the cause of the leak in question (Henshell, 2005b).

Chapter Summary

While academic literature provides numerous important performance analyses of various GR products and benefits, the same sources provide a dearth of information specific to GR failure and the long-term GR maintenance that aids its prevention. Although the internet provides nearly limitless resources, it is often impossible to discern the validity, currency, and balance of information about GR installations, technologies, and BMPs.

In the absence of GR failure rates and operational definitions of GR failure, considerations that resemble failure are cited from a wide range of non-academic industry literature and other industry sources. How other industries approach failure as a routine analysis for system improvement provides a foundation for the thesis research methodology. Process improvement readings have verified that a positive approach to failure analysis includes the pursuit of baseline metrics (which this research hopes to exemplify) as common and essential to industry development and success.

The literature review provides historic and current perspectives about GR applications and a comparison of issues experienced in both green and conventional roofing installations. Industry materials and input from professional GR consultants further provide important clarity about GRs as features separate from the roofs on which they are built. In taking an approach that goes beyond academic papers in this arena, the literature review was elemental to the thesis research because it provided an overview of how GR systems can both succeed and fail, whether partially or, less commonly, catastrophically.

Chapter 4 –Thesis Research

Part I – Developing Green Roof Failure Definitions

To address the lack of an operational definition of failure, this thesis has established a framework and understanding of variations among GR technologies. Categories of GR failure, as well as the interest groups that associate with GRs, have been identified and defined. The literature review aims to support the development and analysis of two thesis surveys, to be discussed in the Research Methodology that follows. Chapter 4 introduces the first of two thesis questions that asks GR experts, "What is the operational definition of green roof (GR) failure?" Part I of Chapter 4 reviews expert responses to the question so that the resulting operational definition of GR failure can be tested in Part II. Survey #2 provides site-related perspectives of failure from GR owners and managers that can be similarly categorized and compared with experts participating in Survey #1.

Research Methodology – Survey #1

Creating agreement on the definition(s) of failure was an important first step toward development of an unbiased analysis of GR failure. To this end, survey #1 sought input from a worldwide consortium of GR representatives. Having a diverse audience of industry interests meant that varied responses could be possible. It was, therefore, necessary to categorize both the industry representatives and the types of failure to allow common points of comparison.

Research Setting – Survey #1

Seeing GR failure firsthand provided additional understanding of issues affecting GR design, installation, and maintenance. The author was allowed access to multiple examples of GR issues at a variety of sites, sometimes in league with the person(s) responsible for managing the structure and/or the individuals involved in the GR's design and installation. Many, but not all, of the sites toured had visible failure issues. Where problems existed, they often involved litigation. Controversy was also mentioned and/or evident between owners and neighbors regarding aesthetics, or reflected issues that unexpectedly burdened the people providing GR maintenance.

Delimitations – Survey #1

To obtain a representative definition of operational GR failure, an online survey using Survey Monkey™ was developed and promoted, targeting experts representing all aspects of the global GR trade and administrators of agency-provided GR incentives. The survey's eight questions were posed over a two-week period and asked participants about issues often associated with GR failure as a result of design, installation, maintenance activities and related to economic and environmental concerns. The survey instrument and detailed analysis of results are posted in Appendix B.

Population – Survey #1

The target population for Survey #1 was developed from several online lists of speakers presenting at international GR conferences held since 2014. Some contacts were accessed via development of the author's LinkedIn™ network. Using a snowball approach, other survey contacts were discovered via web searches, as well as referrals from people who either received and/or completed the online Survey #1. Additional participants responded to the author's post to the currently "suspended" GRiT website managed in Portland, Oregon (http://greenroofthinktank.groupsite.com).

The ability to examine incoming responses via Survey Monkey™ encouraged the author's continued promotion of surveys among expert categories to achieve input from a relatively balanced mix of GR industry experts. The categories included: utility agency representatives engaged in GR incentives; GR trade educators from both the technical and secondary level; urban ecologists whose work benefits wild flora and fauna; and GR industry representatives involved in all aspects of the trade. In this group experts included individuals with experience in GR planning (especially GR architects whose typically central involvement often includes coordination of GR planning and installation, but rarely the maintenance aspects of GR ownership), engineering, installation, maintenance, GR products and manufacturing.

Design - Survey #1

In the interest of creating an operational definition of GR failure, the first survey question posed is open-ended, asking participants to "…provide a general operational definition of green roof failure." Posing an open-ended question before seeking expert association of failure with specifically listed potential GR issues was intentional to obtain each participant's spontaneous answers and reveal the most commonly and subconsciously referenced issues. If questions 2 and 3 were asked prior to question 1, which limit association of failure to specific issues potentially related to GR failure, they would be considered leading information referenced to answer question 1.

Questions 2 and 3 of the survey instrument provided three Likert-style choices with which participants were asked to associate 31 specific potential issues linked to GR failure. Other questions included in the survey asked about the types of incentives, standards, and education offered by a respondent's utility agency or municipality. Although the incentive and standards information may eventually have value, time constraints encouraged the author to forgo analysis of these variables for the short-term.

Sample – Survey #1

Input was obtained from 44 experts who have specialized in GRs for an average of 12 years. Survey participants were subsequently organized into the eight categories listed below. Some respondents qualify for two or more of these categories.

After thee surveys were disqualified, input from 41 experts was evaluated, including:

- **7** Agency representatives involved with GR incentive programs
- **5** GR industry education and marketing representatives
- **5** College faculty specializing in GR-related product performance or economic research
- **3** Specialty growers and horticulturalists
- **4** GR product distributors and related service providers
- **9** Consultants providing general contract design, engineering, installation, maintenance
- **3** Urban ecologists and GR habitat specialists
- **4** GR Owners/managers

Limitations – Survey #1

Analysis of the survey data revealed six incomplete surveys. Two appeared to be unfinished surveys (with secondary restarts completed); two more appeared to be abandoned. Incomplete surveys, deemed to be duplicates by means of IP address and consistently repeated answers, were resolved by excluding the most incomplete survey from the analysis. Two non-replicated but incomplete surveys were kept because they provided spot data (thus the varied "n" values noted in the analysis). One set of participant responses were considered unreliable and were not included because the respondent expressed confusion about the wording of the questions. Other disqualified surveys provided outlying data that was generally opposite of the norm indicating a similar misunderstanding of the questions; and/or provided what appeared to be fatigued, inconsistent, random, or acquiescent answers.

The distinction of GRs as separate from conventional roofs was emphasized within the survey instrument to minimize confounding perceptions among participants who do not differentiate between the roof and the GR, or who perceive the two as one unit. Nevertheless, concern regarding the survey's association of the building membrane and roof beneath the GR was highlighted by five experts who suggested that the survey didn't sufficiently differentiate between these separate components. The lack of data that justifies whether or not the GR is a cause of a membrane failure, however, makes this is a topic for another much-needed study. Despite the concerns, data resulting from the surveys received yield considerable insights into this and other phenomena under study. Questions, comments, complaints, and rebuttals were also posed by four individuals.

In particular, e-mails were received from individuals who had abandoned their surveys or who saw the survey but never initiated a response. Comments received from these experts were either supportive of the failure analysis effort or expressed frustration with the lack of nuance that framed two of the survey questions. These comments are considered in greater detail in the non-response analysis section that follows.

In two instances, key issues cited by respondents to define GR failure do not always reflect the same interests identified by a particular respondent's specific answers to questions 2 and 3. Similarly, some individuals' discrete GR definitions do not associate with the interest(s) the survey respondent has indicated they represent. This complicates survey analysis because it may indicate survey respondents are prioritizing personal beliefs over professional beliefs (or vice versa). It could also be an indicator of survey fatigue or selective non-response (see Non-Response Analysis of Survey #1, below). Overall, the survey is intended to remain open so that additional surveys can be added to the pool of expert GR failure definitions.

Data Analysis – Experts' Definitions of GR Failure

Aggregated results of Survey #1 show industry experts (including long-term owners, stormwater agencies that provide GR incentives, and members of the GR trade) define GR failure as: 1) GRs requiring repeated plant and/or media enhancements before the GR functions as “intended;” 2) failure to meet owner and/or designed intention(s); and 3) leaky membranes (in that order, as summarized in Table 6).

Table 6.
Summary of Experts’ Chosen Issues Associated with Green Roof Failure

Categorized Failure Issues Identified by Experts in Survey #1 – Open-Ended Question #1 Sample Includes utility agencies providing GR incentives, GR industry representatives, and GR owners (in order of priority by all groups)	Count of Respondents **(T n = 41)**
1**. Intended Vegetation, Habitat, and Maintenance**	15
2**. GR Failed to Meet Owner/Designer Intention(s)**	11
3**. Membrane Leaks and Drainage Issues**	17

After coding for words and phrases used by GR experts (as per Hay, 2010), the survey responses were disaggregated and ranked. A comparison between open-ended and specifically defined responses highlights the primary values of GR experts, both individually and as a global industry. The process also illustrates how various issues associated with GR failure as chosen by experts compare to one another. Issues cited regularly by survey respondents were then categorized as indicators of partial and/or total GR failure. The three issues identified in Table 6 appear at about the same frequency as the highest ranked issues in Table 7. The “n” count associated with each concept illustrates how some survey participants answered only selected issues. This variance is seen as reinforcement of the importance of issues chosen more often by the survey respondents.

Table 7.

Detailed Ranking of Experts' Issues Associated with Green Roof Failure (An open-ended question)

Q1. Defining Issues Potentially Associated with Green Roof Failure (an open-ended question)	**Failure Category from Table 5**	**n = Count of Respondents Citing Associated Issue**	**Percent of Total Respondents Associating Issue w/GR Failure**
Vegetation Issues	1	17	43.6%
Owner/Designer Intent Not Met	2	15	33.3%
Design Issues	2	12	30.8%
Membrane Leaks	3	11	28.2%
Aesthetic Issues	2	5	12.8%
Excess GR/Product Maintenance	2	5	12.8%
Habitat Biodiversity	1, 2	5	12.8%
Stormwater Function Not Met	2	5	12.8%
Amenities Not Provided	2	4	10.3%
Green Roof Lacks Habitat	2	4	10.3%
Plants Not Climate-Tolerant	1	4	10.3%
Planting Media Issues	1	4	10.3%
Structure Issues	2	4	10.3%
Drainage Issues	3	3	7.7%
Temp/Sound Insulation Issues	2	3	7.7%
Weeding Management	1	3	7.7%
Amelioration of Urban Heat Island	2	2	5.1%
Economic Issues	2	2	5.1%
GR Requires Replacement	2	2	5.1%
Life Span of Roof Not Extended	2	2	5.1%
GR Installation Issues	2	1	2.6%
Irrigation Issues	1, 2	1	2.6%

Numerically driven definitions of failure. Using a Likert scale, respondents to questions 2 and 3 (Q2 and Q3) were also asked to associate 31 common, hypothetical issues possibly associated with GR failure with three options: whether the issue "DOES associate with GR failure," "Potentially associates with GR failure," or "does NOT associate with GR failure." Ranked results, shown in Table 8, below, highlight a summary of these findings. The ranking shown in Table 8, below, is sorted first on issues chosen by experts that do associate with GR failure (first and eighth columns from the left). This approach provides a numerically driven definition of failure that is slightly different from the spontaneous definitions provided in the open-ended survey Q1.

Outside of failure to meet expert-cited “designed intention,” issues associated with vegetation and leakage revealed by experts’ spontaneous responses in Q1 remain evident as primary issues in Q2 and Q3. What also stands out is the ranking of issues selected by survey respondents. In this case, leaks and media issues were chosen as higher-priority issues than vegetation-related issues. Does this signal a difference between what is promoted and what is believed or known among industry representatives? Questions like this, which evolve from the survey results, are worthy of follow-up analysis but are difficult to fully discern from the data gathered without further industry marketing analysis.

Data otherwise confirms that catastrophic failure is universally understood to be caused by poorly engineered GRs that cannot accommodate the weight of a GR, such as when it is saturated or possibly burdened by snow loads and ice build-up. Less damaging, but still qualifying as total failure, are GRs that leak, causing damage to the structure beneath them or requiring the removal of the GR to repair them. Next ranked are GRs that have problems associated with growth media retention, often because the media has eroded and/or is clogging the GR drainage system. GRs that fail to sustain plant growth (requiring annual replacement of more than 25% of the intended plants) follow next in the ranking. Such replacements exclude rooftop urban agriculture, which, by its nature, involves annual replanting of crops. Proceeding beyond the 50-percent ranking of issues that do associate with GR failure are concerns related to the lifespan of the roof and whether or not, the GR has fulfilled the often-marketed benefit of extending the membrane lifespan.

Table 8.
All Experts' Ranked Issues Associated with Green Roof Failure

1	2	**3**	4	**5**	6	**7**	8	**9**
Concepts Ranked by DOES[(1)] Associate (All Rspndnts)	**Qs 2 + 3 Concepts that Might be Associated w/ GR Failure** (survey respondent chose between three options: Does Not, Potentially, and Does Associate w/ GR Failure) (**bold fonts = highest percentage of responses per issue**)	Rspndnt Count: DOES NOT Associate w/ GR Failure[(2)]	**3rd Ranked %** DOES NOT Associate w/ GR Failure[(2)]	Rspndnt Count: Potential Associat'n w/ GR Failure[(2)]	**2nd Ranked %** Potential Associat'n w/ GR Failure[(2)]	Rspndnt Count: ISSUE DOES Associate w/ GR Failure[(2)]	**1st Ranked** %DOES Associate w/ GR Failure[(2)]	Total Survey #1 Rspndnt Count (n =)[(3)]
1	**GR installation is too heavy for the substructure**	3	8.6%	2	5.7%	**30**	**85.71%**	35
2	**GR leakage has permanently damaged the substructure**	3	8.6%	2	5.7%	**28**	**80.00%**	35
3	**The green roof leaks more than a conventional roof**	3	8.8%	3	8.8%	**27**	**79.41%**	34
4	**GR fails to sustain plant growth**	1	3.0%	6	18.2%	**26**	**78.79%**	33
5	**Poor/no substrate drainage; low drainage outlet, plants drown**	2	5.7%	8	22.9%	**25**	**71.43%**	35
6	**GR leaks are impossible to locate/fix w/o removing installation**	9	26.5%	5	14.7%	**19**	**55.88%**	34
7	**Soil substrates have eroded too rapidly**	1	2.9%	15	42.9%	**19**	**54.29%**	35
8	**Soil substrates clog storm drainage system(s)**	0	0.0%	16	45.7%	**19**	**54.29%**	35
9	>25% of plants require annual replacement	3	8.8%	**18**	**52.9%**	13	38.24%	34
10	**GR fails to sufficiently exceed the lifespan of a conventional roof**	9	28.1%	11	34.4%	**12**	**37.50%**	32
11	GR has a negative effect on property value	**14**	**42.4%**	8	24.2%	11	33.33%	33
12	Nutrients negatively affect stormwater quality	6	17.6%	**17**	**50.0%**	11	32.35%	34
13	GR harbors weeds that damage roof liner	0	0.0%	**25**	**71.4%**	9	25.71%	35
14	GR requires specialized maintenance staff to manage irrigation system(s)	**17**	**50.0%**	9	26.5%	8	23.53%	34
15	GR harbors pests that damage protective roof liner	1	2.9%	**24**	**70.6%**	8	23.53%	34
16	GR impedes resale of property	**18**	**52.9%**	9	26.5%	7	20.59%	34
17	Planting substrate fails to retain 30% or more of average rainfall	11	32.4%	**16**	**47.1%**	7	20.59%	34
18	GR fails to moderate structure's internal temperature	**17**	**51.5%**	10	30.3%	6	18.18%	33
19	GR fails to buffer external noises	**17**	**53.1%**	10	31.3%	5	15.63%	32
20	GR plantings require irrigation to supplement precipitation	**19**	**55.9%**	10	29.4%	5	14.71%	34
21	GR increases insurance rates and/or limits insurance availability	**18**	**52.9%**	11	32.4%	5	14.71%	34
22	GR reduces access to mortgage financing	**18**	**52.9%**	11	32.4%	5	14.71%	34
23	GR doesn't offer cooling benefits to building's neighboring climate	**19**	**59.4%**	10	31.3%	3	9.38%	32
24	GR doesn't offer aesthetic benefits to building occupants	**16**	**50.0%**	13	40.6%	3	9.38%	32
25	GR requires specialized maintenance staff to manage weeds	**18**	**52.9%**	13	38.2%	3	8.82%	34
26	GR return on investment fails to meet target	**17**	**50.0%**	14	41.2%	3	8.82%	34
27	GR fails to filter air and/or water pollutants before draining	13	40.6%	**16**	**50.0%**	3	9.38%	32
28	GR fails to attract beneficial insects and/or wildlife	12	37.5%	**17**	**53.1%**	3	9.38%	32
29	GR installation costs more than initially budgeted	**20**	**57.1%**	14	40.0%	1	2.86%	35
30	Plants "wander" from original planting location(s)	**34**	**100.0%**	0	0.0%	0	0.00%	34
31	Appearance of plantings in dormancy or "off-season(s)" is unacceptable	**30**	**88.2%**	4	11.8%	0	0.00%	34

1. Ranking, initially, by "Does Correlate…" is the basis for data presentation.
2. Concepts and values highlighted with **bold text** represent the highest rank among all three categories throughout the table.
3. Varied "n" values reflect non-responding survey participants in calculations.

Issues that garnered the most expert survey responses are denoted in the table with bold-face font. Issues that follow the 50-percent rankings are deemed to be potentially associated with GR failure or not associated with GR failure. Standouts in this range included issues associated with water quality; less important was the inability of the GR to retain 30% or more of average rainfall (a surprise result, since the objective of many agency GR programs is to enable stormwater abatement and improve downstream water quality via filtration of precipitation).

Other issues that garnered few expert associations with GR failure included the influence a GR has on property values and resale opportunity; lack of return on investment (ROI), including failure to meet project budget; presence of weeds or other pests that might damage the membrane beneath the GR; and lack of amenities provided, such as resolution of UHI issues, temperature and noise insulation, and habitat enhancements. The need for specialized staff to handle irrigation and maintenance ultimately manifests as an issue only potentially or not at all associated with GR failure among GR experts.

Table 9, below, summarizes a ranked frequency of the same 31 potential issues chosen by GR experts. The analysis compares expert selections of the three Likert options associating issues with GR failure. It also segregates issues into categories of “Intention,” “Non-Failure,” “Partial Failure,” and “Total Failure” (intention is discussed below). It is sorted on issues that “Do Associate with GR Failure,” listing in bold the highest chosen values. After 50 percent, the next highest issues selected from the “potentially associated” and “does not associate” survey options are similarly ranked. The table reveals relative agreement among experts with the hypothetical distinction between Non-Failure, Partial Failure, and Total Failure levels established in the section titled “Defining Green Roof Failure Categories”.

Table 9.
Frequency of Expert Selected Issues Associated with Green Roof Failure (ranked by % of issues selected)

Rank of Issue	Issues Potentially Associated w/ GR Failure (bold fonts = highest percentage of responses per issue)	DOES NOT Associated w/ Failure(1)	Potentially Associated w/ Failure(1)	DOES Associate w/ Failure(1)	Total Respondent Count(2) (n=)	Is Issue a Non-Failure, Intention Fail, Partial Failure, or Total Failure?
1	**GR installation is too heavy for the substructure**	8.6%	5.7%	**85.7%**	35	Total
2	**GR leakage has permanently damaged the substructure**	8.6%	5.7%	**80.0%**	35	Total
3	**The green roof leaks more than a conventional roof**	8.8%	8.8%	**79.4%**	34	Partial
4	**GR fails to sustain plant growth**	3.0%	18.2%	**78.8%**	33	Partial
5	**Poor/no substrate drainage; low drainage outlet, plants drown**	5.7%	22.9%	**71.4%**	35	Partial
6	**GR leaks are impossible to locate/fix without removing installation**	26.5%	14.7%	**55.9%**	34	Total
7	**Soil substrates have eroded too rapidly**	2.9%	42.9%	**54.3%**	35	Partial
8	**Soil substrates clog storm drainage system(s)**	0.0%	45.7%	**54.3%**	35	Partial
9	>25% of plants require annual replacement	8.8%	52.9%	38.2%	34	Partial
10	**GR fails to sufficiently exceed the lifespan of a conventional roof**	28.1%	34.4%	**37.5%**	32	Partial
11	GR has a negative effect on property value	**42.4%**	24.2%	33.3%	33	Intention
12	Nutrients negatively affect stormwater quality	17.6%	**50.0%**	32.4%	34	Non-Failure
13	GR harbors weeds that damage roof liner	0.0%	**71.4%**	25.7%	35	Partial
14	GR requires specialized maintenance staff to manage irrigation system(s)	**50.0%**	26.5%	23.5%	34	Non-Failure
15	GR harbors pests that damage protective roof liner	2.9%	**70.6%**	23.5%	34	Non-Failure
16	GR impedes resale of property	**52.9%**	26.5%	20.6%	34	Intention
17	Planting substrate fails to retain 30% or more of average rainfall	32.4%	**47.1%**	20.6%	34	Partial
18	GR fails to moderate structure's internal temperature	**51.5%**	30.3%	18.2%	33	Intention
19	GR fails to buffer external noises	**53.1%**	31.3%	15.6%	32	Intention
20	GR plantings require irrigation to supplement precipitation	**55.9%**	29.4%	14.7%	34	Non- Failure
21	GR increases insurance rates and/or limits insurance availability	**52.9%**	32.4%	14.7%	34	Non- Failure
22	GR reduces access to mortgage financing	**52.9%**	32.4%	14.7%	34	Non- Failure
23	GR doesn't offer cooling benefits to building's neighboring climate	**59.4%**	31.3%	9.4%	32	Intention
24	GR doesn't offer aesthetic benefits to building occupants	**50.0%**	40.6%	9.4%	32	Intention
25	GR requires specialized maintenance staff to manage weeds	**52.9%**	38.2%	8.8%	34	Non- Failure
26	GR return on investment fails to meet target	**50.0%**	41.2%	8.8%	34	Intention
27	GR fails to filter air and/or water pollutants before draining	40.6%	**50.0%**	9.4%	32	Intention
28	GR fails to attract beneficial insects and/or wildlife	37.5%	**53.1%**	9.4%	32	Intention
29	GR installation costs more than initially budgeted	**57.1%**	40.0%	2.9%	35	Non-Failure
30	Plants "wander" from original planting location(s)	**100.0%**	0.0%	0.0%	34	Intention
31	Appearance of plantings in dormancy or "off-season(s)" is unacceptable	**88.2%**	11.8%	0.0%	34	Intention
Rank of Issue	Issues Potentially Associated w/ GR Failure (bold fonts = highest percentage of responses per issue)	DOES NOT Associated w/ Failure	Potentially Associated w/ Failure	DOES Associate w/ Failure	Total Respondent Count (n=)	Is Issue a Non-Failure, Intention Fail, Partial Failure or Total Failure?

1. Concepts and values highlighted with **bold text** represent the highest rank among all three categories throughout the table.
2. Varied "n" values reflect non-responding survey participants in calculations.

Bold-face values are the highest in each category throughout the tables, and show distinct differences between how each interest sector defines GR failure. In particular, industry representatives stand out for citing concerns about leaking membranes, while educators and owners show a stronger concern regarding the effect the GR has on property value and on water quality (more so than agency representatives whose interest in GRs is stated as being driven by water quality and stormwater concerns). Among expert GR owners, issues associated with maintenance and failure to fulfill intended GR amenities also stand out, the last being the second most important issue cited by experts in Q1. These variations may highlight how each group sells its benefits to customers. The differences are worthy of note by non-owners.

The last column of the analysis categorizes ranked issues to a given level of failure (non-failure, partial failure, total failure) as a way to reconfirm the findings and for later comparison with perspectives presented by GR owners and managers. “Intentions,” in this case, are less associated with a GR design than they are potentially related to external outcomes. It is possible that monetary issues associated with older GRs, such as resale, insurability, access to mortgage financing, etc. may have been resolved as GR technologies have advanced.

Failure Definitions by GR representation. Table 10, below, summarizes fully ranked comparisons of the same 31 potential issues as chosen by categories of GR experts using the same Likert scale results shown in Tables 7 and 8, and compares the bolded and ranked sorting of issues that “do associate with GR failure” with the chosen values among each category of GR representation (note that some individuals chose to answer only selected questions, thus the variable “n” values in tables).

The Likert association of issues with failure in GRs provides a numerically driven definition different from the spontaneous definitions provided for the open-ended Q1. Although the analysis would benefit from a higher participation of experts in each of the

Table 10.
Experts' Ranked Association of Issues with GR Failure, by Affiliation

Rank based on DOES[6] for All Survey Ptcpnts	**Qs 2 + 3 Defining Issues - Might Correlate w/ GR Failure (survey respondent chose between three values: Does Not, Potentially, and Does Correlate w/ GR Failure)**	**Respondent Count: DOES Correlate w/ GR Failure** (n =)	**Ranked % of ALL Respondent's Choice of DOES correlate w/ GR Failure**	**Agency[1] Rep's Choices Ranked % by DOES...** (n = 7)	**Education Rep's[2] Choices Ranked % by DOES...** (n = 7, 8)[5]	**Industry Rep's[3] Choices Ranked % by DOES...** (n = 16, 17, 18) [5]	**Owner Rep's[4] Choices Ranked % by DOES...** (n = 4)
1	GR installation is too heavy for the substructure	30	**86%**	86%	**88%**	**92%**	75%
2	GR leakage has permanently damaged the substructure	28	**80%**	**100%**	75%	**100%**	75%
3	The green roof leaks more than a conventional roof	27	**79%**	**83%**	**100%**	**91%**	75%
4	GR fails to sustain plant growth	26	**79%**	50%	14%	40%	50%
5	Poor/no substrate drainage; low drainage outlet, plants drown	25	**71%**	57%	0%	54%	**75%**
6	GR leaks are impossible to locate/fix w/o removing installation	19	**56%**	33%	57%	**91%**	50%
7	Soil substrates have eroded too rapidly	19	**54%**	29%	50%	**62%**	25%
8	Soil substrates clog storm drainage system(s)	19	**54%**	43%	**75%**	46%	25%
9	>25% of plants require annual replacement	13	**38%**	17%	14%	**50%**	**100%**
10	GR fails to sufficiently exceed the lifespan of a conventional roof	12	**38%**	**1.00%**	**57%**	**82%**	**100%**
11	GR has a negative effect on property value	11	**33%**	**43%**	**38%**	36%	**50%**
12	Nutrients negatively affect stormwater quality	11	**32%**	33%	29%	**50%**	25%
13	GR harbors weeds that damage roof liner	9	**26%**	14%	**38%**	25%	0%
14	GR requires specialized maintenance staff to manage irrigation system(s)	8	**24%**	0%	29%	25%	**50%**
15	GR harbors pests that damage protective roof liner	8	**24%**	0%	**57%**	27%	25%
16	GR impedes resale of property	7	**21%**	**43%**	13%	17%	25%
17	Planting substrate fails to retain 30% or more of average rainfall	7	**21%**	0%	14%	25%	**50%**
18	GR fails to moderate structure's internal temperature	6	**18%**	14%	13%	0%	**50%**
19	GR fails to buffer external noises	5	**16%**	0%	14%	0%	**50%**
20	GR plantings require irrigation to supplement precipitation	5	**15%**	0%	14%	17%	**50%**
21	GR increases insurance rates and/or limits insurance availability	5	**15%**	14%	13%	**25%**	0 %
22	GR reduces access to mortgage financing	5	**15%**	**29%**	13%	**25%**	0%
23	GR doesn't offer cooling benefits to building's neighboring climate	3	**9%**	0%	14%	0%	0 %
24	GR doesn't offer aesthetic benefits to building occupants	3	**9%**	0%	0%	10%	0%
25	GR requires specialized maintenance staff to manage weeds	3	**9%**	0%	14%	8%	**25%**
26	GR return on investment fails to meet target	3	**9%**	14%	13%	0%	0%
27	GR fails to filter air and/or water pollutants before draining	3	**9%**	0%	0%	10%	**25%**
28	GR fails to attract beneficial insects and/or wildlife	3	**9%**	17%	14%	10%	**25%**
29	GR installation costs more than initially budgeted	1	**3%**	0%	0%	**8%**	0%
30	Plants "wander" from original planting location(s)	0	**0%**	0%	0%	0%	0%
31	Appearance of plantings in dormancy or "off-season(s)" is unacceptable	0	**0%**	0%	0%	0%	0%

1) "Agency" representatives: include survey respondents having a direct affiliation to a municipal utility providing GR-related incentives.

2) "Industry Educator-Practitioners" includes high profile individuals involved with GR trade, policy development, and/or public outreach, education.

3) "Industry Practitioners" include respondents involved in GR planning and installation, as well as urban ecologists. Where a respondent did not provide identifying status and where online research did not reveal more information, this is where they were counted.

4) Four "Owner and Manager" representatives include 3 respondents involved with GRs installed on public buildings where low bid projects are the norm (2 respondents are from 1 site w/ total failure issues, the 3rd and 4th are high-profile proponents of GRs).

5) Varied "n" values reflect non-responding survey participants in calculations.

categories, distinct differences among the different sectors of the GR industry nonetheless emerge from the data. These sectors include a total count of individuals in each of the following categories:

- **7** Municipal agency in the U.S. representatives incentivizing GRs for ecosystem services
- **8** Educators representing both GR industry organizations and secondary academic institutions in North America and abroad
- **15** Industry representatives providing GR planning, products, and/or services
- **4** GR owners and managers who were involved with GR planning, installation and long-term management

Seven (7) educators were additionally disaggregated from the survey participants listed above because of the consistent differences in their responses relative to the various categories. The educators group includes individuals specifically affiliated with academic and GR industry training efforts, as well as high-profile GR professionals who are directly involved in developing the GR trade education benefitting consumers and agencies alike.

Non-response analysis – Survey #1. Given a worldwide population of GR experts, more than the 30 minimum surveys would be needed to pursue a statistically relevant analysis. Additional input to the definition of GR failure will be beneficial to help distinguish details from one aspect of the GR trade to another, but the responses gained are considered sufficient. Q2 and Q3 of Survey #1 prompted experts to associate specific issues associated with GR failure. Not surprisingly, comments made by three survey non-respondents indicated a need to better distinguish GR "intention" and disagreement with the relative "lack of nuance" in these questions (see Appendix B). This is exemplified by the following quotes from e-mails sent directly to the thesis survey author:

> *I think you need an additional response category—something to the effect of "depends on roof specifications" or "Indicates roof failure if [____] was a part of the roof system design." Many of the things you have listed as "failure" depend on the design intent or functional intent—for example, weeds may or may not be a problem depending on the*

design intent; whether a roof retains 30% of the annual precipitation or not as an indicator of failure depends on what the roof was designed to do. If, for example, it is a thin 1" thick roof designed for aesthetic reasons, it may not matter how much water is retained, etc. If the roof is being done to comply with stormwater regulations and it provides sufficient retention to comply without plants, then a total loss of plants may not constitute a failure.
(personal communication, Dr. Robert Berghage, director, Center for Green Roof Research, Penn State University, February 15, 2016)

Green roof failure, in my opinion, is very site- and design-specific. A green roof in coastal Washington State will be substantially different than one in California's central valley. A green roof intended primarily to moderate temperature on a building with substantial loading constraints should be evaluated differently than a rooftop farm [a.k.a. "urban agriculture"]. Certainly, some of your failure conditions are universal, like premature leaking. // I started to feel like my answers to your survey didn't allow for this kind of nuance...to the point that answering them could be misleading to you. Someone once told me that a green roof fails when "the plants die, the roof leaks, or the building falls down.
(personal communication, Kent Thompson, GR contractor, California, February 5, 2016)

It is possible that the concerns regarding nuance was reason for some people to not participate in the survey, for other participants to discontinue completion of their surveys, or for participants to respond only regarding the most important failure issues from their perspective (thus the varied "n" values).

Green roof failure definition categories. The "partial," "total," and "catastrophic" failures hypothetically defined in Chapter 2 are considered again in Table 11. This time, an understanding of concerns among the primary interest groups identified that influence or otherwise relate to GRs, is fully established. The data provided here are summarized from coded expert responses to Survey #1.

Table 11.
Defining Gradations and Issues Associated with Green Roof Failure

Severity and/or Duration of GR Failure	Potential Issues Associated with Failure Type
Partial GR Failures **transitory issues** repairable without GR removal	1. Client-stated dissatisfaction, whether related to aesthetics, maintenance, or other issues.
	2. GR safety issues associated with access not addressed in original GR design/engineering plans.
	3. Warranted and other repairs (needed w/in warranty period) and/or temp. GR removal, regardless of cause.
	4. One-time plant failures involving < 25% of installed, occurring within 1–3 years.
	5. Cost overruns, not collectively exceeding the customer's stated cost definition for a major failure, associated with GR, but not the membrane beneath it.
Total GR Failures **entrenched issues** tend toward GR removal or involve major GR or roofing membrane repairs	1. GR-related cost overruns that collectively exceed the customer's stated cost for major failure of the GR.
	2. Structural leaks, regardless of cause or association with GR relative to the roofing membrane beneath it.
	3. GR drainage issues resolved with GR removal.
	4. Multiple failures > 25% of installed plants occurring within 1–3 years.
	5. Repeated partial failures.
	6. Any partial fails listed that escalate into temporary or permanent GR removal.
	7. Owner pursuit of litigation to recover costs related to failures listed above.
Total and Catastrophic GR Failures limited to structural failures, re-built GRs and total GR removals	1. Related to ineffective GR engineering.
	2. Permanent structural damages associated with membrane failures (leaks).
	3. Permanent GR removal.

Summary: Part I

Internationally respected Wolfgang Ansel provided the following input via e-mail that begins to summarize a primary and overarching theme among GR experts:

> *From my point of view, a green roof failure occurs if the targeted conditions in the contract between the green roof installer and the building owner are not reached.* (personal communication, Wolfgang Ansel, International Green Roof Association, Germany, February 15, 2016)

Green roof failure depends upon who defines it. Failure criteria obtained from experts worldwide who responded to thesis Survey #1 provide a diverse cross-section of perspectives. Disaggregation of responses from the three primary interest groups (municipal utility representatives who provide GR incentives, GR industry marketing interests, and GR owners or managers) into failure categories is helpful to the creation of an operation GR failure definition. These categories (non-failure, partial failure, total failure, and total/catastrophic failure, as defined in Chapter 2) are based on the severity of the failure and whether or not the failure is entrenched or can be overcome within a particular period of time.

Although ranking of primary issues by experts reduces to the categories of design intent, vegetation, and leaks, disaggregation of expert responses into categories represented by public agencies providing GR incentives, GR industry representatives, and GR owners and managers, plus a separate category of educators, provides an alternative failure perspective that can be aligned with the results of Survey #2 (to be discussed in Part II, and in Chapter 5).

Agency definitions, implied in part by Portland's list of GRs, include the same understanding of other interest groups regarding structural collapse as a total or "catastrophic" form of failure. This failure is different, however, from the less severe "total" failures associated with leaks and temporary removal of a GR. Agency failure interests are otherwise limited to stormwater and/or energy efficiency objectives, but do not include the breadth of failure of related to aesthetic and functional amenities typically promoted to potential GR owners by GR industry or education interests.

The failure definitions of GR owners and managers, (as well as educators), include expectations of year-round aesthetics that can unknowingly contradict an owner's interest in minimal maintenance, among other benefits not always guaranteed with the installation of a GR. This is evident among survey responses submitted by managers who have been tasked with maintenance of publicly owned GRs, as well as owners and managers who have limited horticultural training. In addition to plant selection and product performance, educators appear to have an interest in preventing the clogging of drainage systems by planting media, a value that may be indicative of research or funding priorities.

Among GR industry representatives are GR designers whose definitions of failure tend to focus more on aesthetics and on GR maintenance involving irrigation and weeding, a topic with which owners are also more concerned. Product providers, on the other hand, can be expected to compete in the development of technologies that are easily produced and installed. Provision of amenities by GR industry representatives also ranks, but not always as highly as the technologies themselves.

By way of the expert survey and communications with GR trades experts, all interest groups appear to consider GR longevity a more important benefit than stormwater management. Verification of this promoted outcome, however, will require time to manifest. Given the GR trade is still somewhat young, product longevity has yet to be fully tested in North America and elsewhere. This insight was reiterated in a recent Portland infrastructure audit report (Caballero, Kahn, & Prinz, 2016, p. 8).

Part II – Application of Definitions and Criteria

Having established a definition of GR failure with the aid of expert input in Part I of Chapter 4, the second phase of the research involves a case study of the more than 500 GR sites located in Portland, Oregon. Part II of Chapter 4 provides details on how the criteria from the first survey are applied to GRs in Portland, Oregon. Here, GR owners, managers, or GR representatives associated with institutional, commercial, and industrial (ICI) installations participated in a survey prepared to elicit an answer to the second research question: "Do experts' definitions of green roof failure match those of GR owners and managers?"

Survey #2 was created separately from the expert-driven Survey #1 and provides data that establishes a unique owner/manager perspective of GR failures. Portland representatives provided responses regarding failure relative to the particular GRs that they manage. To the degree that the definitions of GR failure overlap between the two surveys, similarities among all interest groups in defining GR failure, as well as the differences between them, are important.

Survey #2 also allows the application of the expert-derived definition of GR failure to a population of GRs that is considered more or less representative of other municipalities which incentivize GRs for the sake of stormwater management benefits. Data provided by City of Portland Bureau of Environmental Services (COP/BES) enabled the survey completion, but also demonstrates the data population process that can reinforce numerically-driven asset management of GRs.

Case Study Application in Portland, Oregon

This observational survey (see Appendix C for an overview of the instrument and responses) is quantitative in nature and assesses institutional, commercial, and industrial (ICI) participant perceptions of costs associated with major repairs in the interest of first identifying and categorizing issues known to or experienced by each survey respondent relative to the GR they own and/or manage, or with which they are affiliated.

Portland, Oregon, was an attractive and convenient case study because of its proximity and the quality of its available list of GRs. Portland's data set is replete with mostly current information, including installation addresses and some owner/developer contact information. Seattle, Washington's population of GRs was also attractive because of proximity, but the data there is not yet fully associated with GIS and/or street addresses, as is the case in Portland and Chicago, Illinois. The decision to focus survey efforts in Portland was further confirmed after unsuccessful survey attempts were made among the 300 ICI GR sites located in Chicago. Survey completions in Chicago were not readily forthcoming because contacts there are not as well defined as Portland's. Multiple calls were required before reaching an individual who might be associated with GRs at locations where addresses have periodically shifted under new owners.

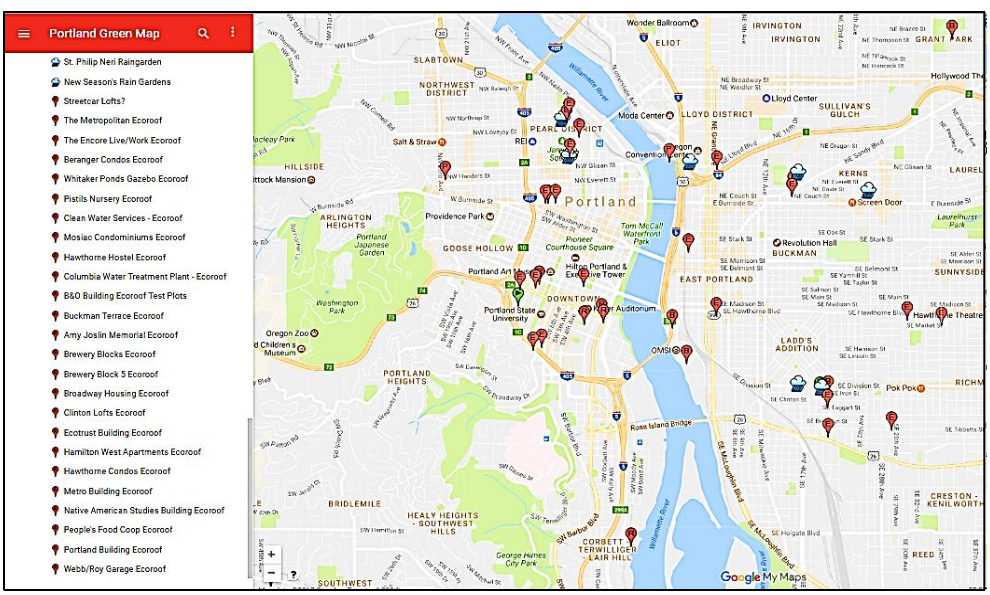
The list of GRs provided by COP/BES comes with a 2010 date, but includes GR data from 2016. Its relative completeness provides a preliminary example of how agencies might manage the recording of GR assets and promotion of GR installations elsewhere in North America. Among a variety of other data, the list implicitly identifies failure criteria at most locations by referencing GRs that have been removed and/or reinstalled.

Research Setting - City of Roses

Portland, Oregon's 2015 estimated population of 632,309 (U.S. Census Bureau, 2016) defines it as the 26th most populous city in the United States. Approximately 60 % of Oregon's overall population resides within this economically vibrant metropolitan area (Gowdy, 2010) which covers 145 square miles (380 square kilometers).

It is well known that Portland establishes trends for the rest of the nation. Like the city of Chicago, Portland's eco-friendliness is also elemental to its political commitments. According to the Urban Mobility Corporation, “The city government is notable for its land-use planning and investment in public transportation” (Orski, 2003). An additional dedication to locally grown food and preservation of open space make Portland one of the world’s “greenest” cities (Grist Staff, 2007). Portland offers a diverse culture that attracts technologically oriented Gen-Xers seeking highly paid work in a sustainably oriented urban center that offers opportunities for both work and play. International GR advocate Sabine Frueh refers to this affiliation with technology as “a knowledge work economy [where] people are the engine that keeps companies growing, adapting, improving, and innovating (Frueh, 2016, p. 2).

Over 600 vegetative roofs are installed on large, small, old, and new residential, industrial, and other public and private buildings. A regularly changing Google Web® map (illustrated in Figure 13) shows a partial selection of Portland’s green infrastructures, and includes vegetative roofing installations in the city and beyond. Of the 145-square-mile (380 square kilometer) area spanned by the city at the date of thesis publication, GRs cover nearly 24 acres (roughly 9.7 hectares; less than half of one square mile, and equivalent to roughly 3 percent) of the total roofs that shelter homes, businesses, industries, and storage areas.



Source: https://www.google.com/maps/d/viewer?mid=1FrHIHnm6Od-iLl_YQrU4qSW5iZw&hl=en&ll=45.47615457115366%2C-122.41731276025394&z=11

Figure 13. Google map of green infrastructure in Portland, Oregon.

Portland's climate and need for GRs. The mild climate in Portland offers residents generally warm to hot, dry summers and chilly, rainy winters with mean high and low temperatures of 70 °F (21.1 °C) and 41 °F (5 °C), respectively. Historical records suggest that summer precipitation averages barely 6 inches (15.24 cm) between the months of June and October, with the highest rainfall occurring in December (timeanddate.com, 2016). Historic records also suggest that winter precipitation averages around 29 inches (73.66 cm), mostly in the form of rainfall, but sometimes snow and ice (World Meteorological Organization, Region IV - North America, 2016). Climate changes are beginning to confound the historical data, however, with a record-breaking 90-day drought occurring in 2015 and near record-breaking winter weather occurring in the winter of 2016 (Pierce, 2016; Templeton, 2015).

Context for GRs in Portland. Interest in GRs was originally spurred throughout North America following the publication of BMPs that preceded federal stormwater mandates in the U.S. (Schueler, 1987). Portland, Oregon's GR green infrastructure story is built upon the same 1989 U.S. EPA Surface Water Treatment ruling applied in Portland, Maine, mandating stormwater management (Talberth & Hansen, 2012). Like most urbanized areas, Portland's ground plane was already developed to the point that nearly every surface was impermeable to precipitation. Combined sewer overflows (CSOs) were also polluting local water bodies (U. S. EPA, 2012). Treatment and dispersion of stormwater on site has since become a primary green infrastructure objective, achieved by either letting stormwater stay on site long enough to percolate into compacted or paved-over subsoils (which also benefits groundwater replenishment) or by allowing it to evaporate from exposed soils and/or transpire from planted and other foliage (personal communications, T. Liptan, January 25, 2017).

GR technology is not merely a trend in Portland. It is a necessary pursuit in response to the typically ample winter rainfall, which exacerbates combined sewer overflows in Portland's wastewater utility infrastructure (David Evans & Associates, 2008). By acting as a temporary sponge on top of buildings, Oregon's "ecoroofs" are meant to provide privately engineered and managed stormwater infrastructure services.

Landscape architect Tom Liptan is the originator of the city's ecoroof program. Starting in 1996, the program has continued beyond his retirement in 2013. Liptan originally suggested the use of green infrastructure (GrIS) in the form of rain gardens to obtain stormwater abatement and filtration while working with engineers who were familiar only with the pipes and pumps of conventional stormwater (a.k.a. "grey") infrastructure in 1995. Shortly thereafter, Liptan reported being inspired by a Belgian soap label indicating that because the soap was made in a factory with a GR, it was more sustainable than products produced in facilities without a GR.

Having his interest piqued by this social marketing strategy, Liptan took up GR research on his garage roof in 1996. He was later granted utility funds to test the stormwater management potential of developer-installed GRs that met his plant and media specifications. Liptan wanted to illustrate the costs and benefits of low-input vegetative roofing in Portland. Continued research and reporting on climate change and the related need for infrastructure expansion, plus limited area for rain garden installations, has since then opened infrastructure considerations to the concept of GRs and GrIS world-wide.

In 2003, Portland ER performance evaluations demonstrated that up to 69 percent of stormwater could be abated from a [dry] installation (Hutchinson, Abrams, Retzlaff, & Liptan, 2003). The same kind of analysis, repeated in 2008 on three additional ERs (Spolek, 2008), found average annual rainwater retention rates ranging between 12 and 42 percent. Gangness and MKA issued a report in 2007 in the similar eco-region of Seattle, Washington, and another Portland report by Cardno/TEC in 2012 offered findings from the comparison of GR media options, which confirmed the potential of vegetative roofing for stormwater management. Developers in both Portland and Seattle were early adopters of GR technologies who aided the commercialization of the GR industry, supported twice per year by Liptan's organization of public education events, (personal communications, T. Liptan, January 25, 2017; personal communications, T. Liebow, August 22, 2016).

As a pioneer in the development of GR incentives, however, Portland's GrIS programs were periodically challenged. Litigation targeted the City of Portland's Bureau of Environmental Services (COP/BES) for allocating an increasing amount of rate-payer funds to what was considered unproven technologies, including ecoroofs (Har, 2010; Anchell, 2011). Local media also pushed back when early GR failures became evident. Total GR failures (as defined in this thesis) were evidenced on three of the largest installations in downtown Portland (Geneovese, 2008; Sturrock, 2010). Older buildings, such as these, represent a more difficult and expensive effort to engineer GR installations that are both safe (especially in an earthquake) and create positive drainage on roofs that lack it. A measure of the number of older buildings in Portland in terms of truly available and cost-effective roof space for GRs might be sobering, and presents a research opportunity tangential to this thesis.

Two of the early program failures involved the re-engineering of older buildings where poor drainage of the intended GRs went unaddressed. Architectural experts also specified unsuitable plants in soil media that would be stressed by a lack of summer irrigation. Soils were deemed to be over-engineered by GR designers who assumed that the plants would not survive in anything less than a high percentage of organic matter. While damage to either building via leaks was not mentioned, both highly visible plantings experienced major plant losses. Plants chosen for drought and sun tolerance were subsequently drowned in standing water after two reinstallations on one of these structures, and remain challenged today on the second despite media refurbishment and replanting attempts with different species. Both of these projects were recipients of an unreported amount of public funds.

Undaunted, members of the fledgling North American GR industry have refined planting and media specifications originally established in Europe, highlighting the differences that eco-regions can impose upon the effective development of GRs everywhere. Although the "market for GRs appears to be shrinking," (personal communications, P. Carey, March ??, 2017), GR advocates still collaborate to develop effective incentive and program outreach strategies that aim to overcome disparate marketplaces that are different from the locally driven GR supply-to-market opportunities seen in smaller European locales.

Among the specific benefits promoted by COP/BES, ecoroofs impede flow of precipitation, filter precipitation draining from vegetated rooftops, and minimize downstream scouring of otherwise fast-running waters (Stiffler, 2011; VanWoert et al., 2005). GRs minimize the amount of stormwater entering the system linked with the sewer lines, which are periodically overwhelmed by precipitation, causing combined sewer overflows (CSOs) (COP/BES, 2005). COP/BES also has an interest in creating habitat in the form of GRs for the sake of pollinating insects and both native and migratory birds (Cunningham & Liebezeit, 2015).

In 2014, the chart shown in Figure 14 was posted on the internationally sponsored website Greenroofs.com. The chart provides an excellent summary of the types of GRs recorded in the Portland area by COP/BES.

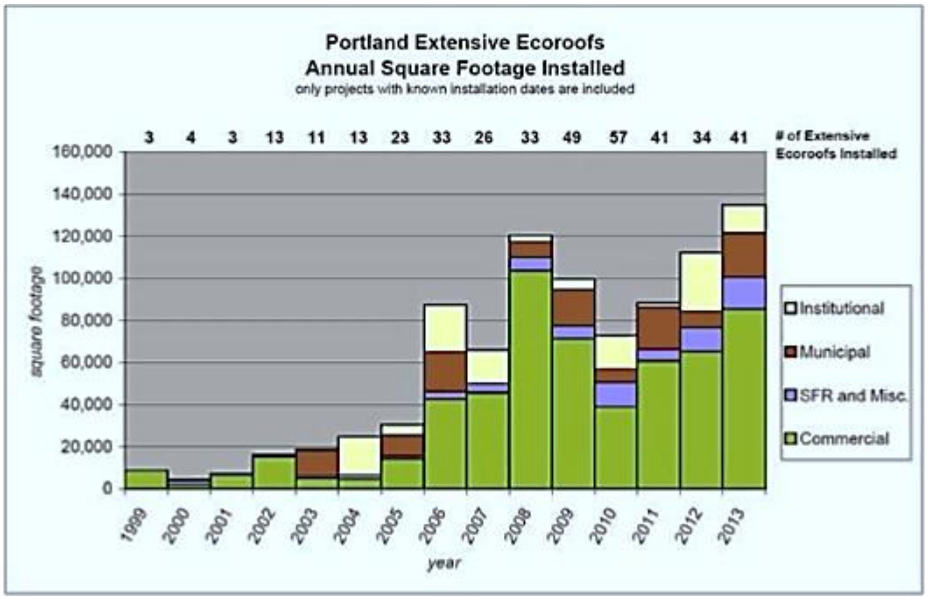
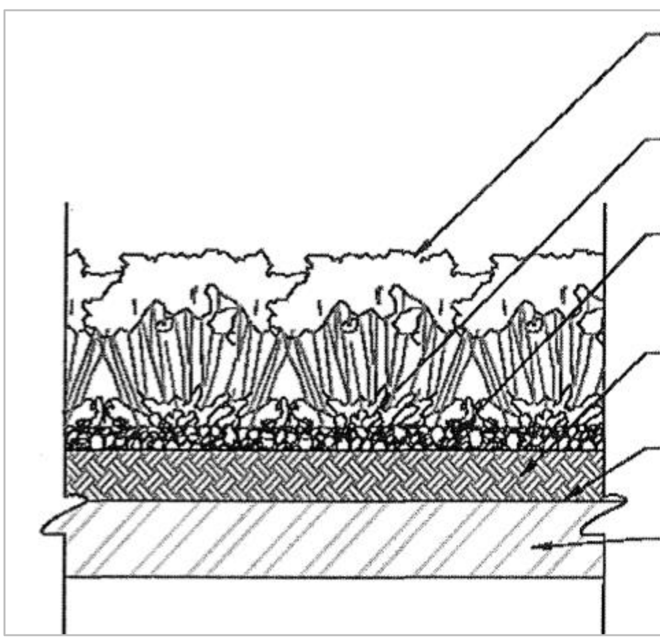


Figure 14. Record of ecoroof installations in Portland, Oregon, as of January 2014.

Around the same time the data in Figure 14 was posted, a revision was made to the COP Green Building Code, which includes a cross-section illustration of the simplified type of ecoroof that Liptan and his associate Brian Weddington co-designed (Figure 15; COP/BES, 2016, p. 11).



- FLOWER BRACKET PROVIDES BEAUTY IN THE SPRING AND SUMMER, SHADE TO PROTECT PLANTS IN LATE SUMMER, AND FOOD AND HABITAT FOR WILDLIFE IN THE WINTER.
- SEDUM CUTTINGS INSTALL AND ESTABLISH QUICKLY, ARE ADAPTED TO DROUGHT AND MOISTURE, AND MOST DO NOT GO DORMANT.
- RED CINDER MULCH, ALONG WITH VEGETATION, PROVIDES LONG-TERM SOIL PROTECTION, WHILE RETAINING SOIL MOISTURE AND MODERATING SURFACE TEMPERATURES.
- SOIL BALANCES DRAINAGE WITH MOISTURE RETENTION. RATIO OF SOIL/MULCH IS VARIABLE WITH STRUCTURAL CAPACITY.
- PROTECTION/MOISTURE MAT (OPTIONAL) GUARDS WATERPROOF MEMBRANE AND CAN PROVIDE MOISTURE LAYER.

Figure 15. Red cinder green roof design specification (text reproduced, as developed by Tom Liptan in association with Brian Weddington for the City of Portland Green Building Policy).

Among the Portland installations developed by Liptan and visited in August 2016 for the thesis research, all were recently weeded and subjectively considered to be naturalized, but aesthetic. Most of these ecoroofs were mature, installed on large, relatively flat industrial and institutional structures, contractually managed using manual removal of weeds on a 2x–6x/year basis (some are weeded once every 2–3 years), and are not regularly accessible to the public. Only one of these roofs was situated in a location where people inside the building would view it. None of the ecoroofs toured were eroding or barren of plant materials.

Conventional GR aesthetics are not a priority cited by Liptan as important, compared to the priorities of creating a regionally adapted and natural ER appearance that provides important stormwater eco-system services. Most of Portland's ERs, however, do provide visual relief in their fairly uniform and naturalized growth, which incorporates contrasting colors and textures. The ERs that sported more "weedy" grasses also showed also more signs of desirable insect and bird visitation.

A tour of the ER on top of the Portland Building showed evidence of challenges by various failure-associated issues: siloed politics, a history of burial under tarps containing construction debris, and abandonment of the irrigation system after the 12-inch PVC irrigation system risers were broken by visitors. When seen in August 2016, however, this ER displayed a healthy spread of somewhat dormant low-growing grasses and aesthetic drought-tolerant weeds among the few sedums remaining from the second refurbishment provided several years earlier. Although this ER is a shadow of its original grid layout, it looked like a mature meadow and hosted the best example of biodiversity of the installations visited. Although "weedy" species existed, the planting successfully fulfilled this site's stormwater management objective.

This is a non-accessible site, however, that didn't need to look polished. By conventional aesthetics standards, it may only have garnered a rating of 3 or 5 out of 10, depending upon one's personal preference for a dense carpet of lush plantings and layout perfection. Others might have judged it based on its perceived potential to become a fire hazard. While the fear that drives that concern is understandable, the potential for fire hazard, at least in low-growing GRs, and especially in irrigated GRs, is counterintuitive and has been scientifically disproven (Breuning, 2008; Oberndorfer et al., 2007; Peck & Kuhn, 2001). Other individuals, however, consider the ER at this location a contributor to the leaks that have plagued this historic building

Portland's Green Roof Policies and Incentives

Since 2001, Portland has exemplified progressive sustainability standards to its own community and others by implementing a Green Building Code. The intention of this policy is to minimize environmental impacts related to the construction, operation, and maintenance of new and recently installed city building assets and enhance employee health and productivity while minimizing long-term expenses (City of Portland, 2015). According to a U.S. Department of Energy summary, the policy also requires participants to "include an ecoroof with at least 70% coverage, high reflectance and Energy Star-rated roof material on any non-ecoroof roof surface area." (U.S. Department of Energy, n.d., summary page).

Although the use of other engineered GR designs is allowed, the illustration shown in Figure 14 is the ER approach considered among the best at meeting COP/BES stormwater objectives as promoted by the city and by others managing COP/BES ecoroof incentives (personal communications, A. Chomowicz, March 13, 2017). Specific to the policy and related policy audits are LEED certification objectives determining the long-term costs associated with the Green Building Code (Caballero et al., 2016). This last reference supports the development of a baseline rate of GR failure that can aid in better meeting the long-term cost accounting goal of asset managers who report on Portland's infrastructure assets.

Over the years, COP/BES has offered two incentive programs to encourage the installation of ERs and GRs in Portland to enable the extension of the city's stormwater infrastructure. A 2012 presentation made to Green Roofs for Healthy Cities attendees highlighting the city's GRs references both stormwater and energy benefits (Miller & Liptan, n.d.), indicating incentives have also been offered by Portland's Office of Sustainable Development. For this branch of the City agency, GRs enhance the function of solar photovoltaic (PV) panels.

The acronym for the most commonly obtained incentive is "G2G," which stands for Grey to Green. "FAR" is the acronym for the second incentive, which stands for Floor to Area Ratio. Both incentives are implemented by municipalities across North America and promoted at annual industry conferences; however, the incentives are locally managed and regulated.

Starting in 2008, the Grey to Green (G2G) incentive was offered in Portland over a five-year period to complement the installation of a $1.4 billion stormwater system improvement project (the "Big Pipe"), as well as Portland's 2005 Watershed Management Plan (COP/BES, 2005). The Big Pipe was engineered to keep 1.76 million gallons of untreated sewage mixed with stormwater from entering Portland's Willamette River and other local waterways. The incentive, which was scheduled to be discontinued in 2013, provided $5 per square foot of GR or ecoroof installed (Stiffler, 2011). COP/BES reported that it "…granted almost $2 million in incentives that helped fund over 130 projects that created more than 8 acres of ecoroofs that [theoretically] manage an average of 4.4 million gallons of stormwater annually (COP/BES), 2012)." Portland currently links the installation of GRs receiving G2G incentives to property deeds (personal communication, Hoy, March 13, 2017). These deeds require that whatever entity assumes ownership of a building with a GR will maintain the asset, and minimizes removal of the GR and ER installations.

Portland's Floor to Area Ratio (FAR) standards have been made available since 2009 and apply maximum and minimum ratios of constructed residential to parking and commercial structures in designated neighborhoods. These standards are intended to "…coordinate private development with public investments in transportation systems and other infrastructure, limiting and stepping down building bulk [in proximity] to the Willamette River, residential neighborhoods, and historic districts"(COP/BES Services, 2009). This incentive will sunset in 2017, becoming a zoning code requirement (personal communications, R. Hoy, March 13, 2017).

When combined, incentive outcomes are attractive to developers considering inclusion of vegetative roofing, among other GrIS options, to accrue LEED points. Benefits of installing a nominal square footage of GR, for example, include a higher level of certification and marketing publicity. The incentives essentially allow developers to build and more competitively market higher and/or wider structures than are normally allowed. This kind of real estate square footage can make or break a developer's profit margin. The ROI value of real estate in LEED structures is high and such buildings maintain investment returns well into the future. Marketing vegetative roofing installations thus makes sense, but can alternately lead to over-commitment (and potential GR failure) by owners and designers who lack familiarity with the long-term maintenance obligations that these projects require.

Data Management and Transparency

Distribution of the two incentives outlined above is recorded in Portland's list of GRs. Some, but not all, financial incentives provided to developers installing GRs on dates preceding the G2G and FAR incentives are not recorded, however. Evidence verifying earlier incentives is maintained separately by COP/BES in periodic reports, or was discovered in media found online regarding Portland GRs experiencing failure issues. The degree that alternate funding for early GR installations is unknown is also noted in the non-response analysis section of this chapter.

Among web-sourced findings of GR failure in Portland are three sites considered "experiments" by Liptan (personal communication, T. Liptan, January 25, 2017). Two of these sites required more than one reinstallation; one of them required two reinstallations, and both apparently still suffer from lackluster plant performance. City-sourced or managed funding associated with these projects is substantial and would require recording if failure analysis were fully instituted in Portland. Even if these preliminary installations were deemed "experimental" and encountered failure issues, their costs and performance data are educational.

Research Methodology – Survey #2, Observing Green Roof Failures

The second survey is quantitative and observational in nature and uses the professional level of Survey Monkey™ to enable more than 10 nuanced survey questions, plus a greater variety of post-survey analysis. As noted previously, this survey targeted ICI owners and managers of GRs to facilitate a measure of the failure rate among ICI sites within Portland, Oregon's urban setting. A random survey sample was sought, but the result is more aptly considered a convenience sample.

The survey instrument posted in Appendix C shows questions pertinent to the thesis discussion. Omitted from the instrument displayed are questions related to the differentiation of GRs in Portland from those in Chicago, Illinois, as that portion of the thesis investigation was curtailed. Omissions also include a question scripted to measure the costs of GR removal. This question was a fruitless pursuit because most respondents did not know the total value of their respective GR.

Survey #2 was originally meant to be administered online using a Survey Monkey™ template, but the need for nuance forced reconsideration that favored telephone interviews. The thesis author, who is informed and conversant about GRs and failure issues, wanted to engage survey participants to overcome the nuance issue while gauging participant familiarity with their representative GRs. The surveys were eventually implemented as a consistently worded script and the Survey Monkey™ cloud-based system was used as a data repository.

Population – Survey #2

The second survey targeted a sample of 204 institutional, commercial and industrial (ICI) GR owners or managers. Most contacts were made possible by a mixed list of nearly 500 GR installations obtained via public information request from COP/BES. Prior to completion of this list, six sites were added, deemed official via the COP/BES website. Three of these additions were commercial-residential, one was a mixed-use commercial site, another was a large municipal utility site, and the last was a small municipal utility site parsed out of the list from a cluster of data because the project was significant in scale and media evidence was available about it online. Not included on the list were four sites dedicated to freeway "LIDs," which comprised 52,000 square feet of low-maintenance GRs. Four "urban agriculture" sites were included in the survey, although retrospective consideration suggests that many of these are not representative GR installations. Both these and the highway LIDs represent data that may potentially skew the research. For this reason, the urban agriculture site data has periodically been excluded from data analyses.

Focusing only on ICI GRs proved beneficial because there are fewer privacy-related issues associated with these sites than with residential installations. In addition, the variation of ICI GR installations is not nearly as broad as residential GR installations. The survey effort was a full-time pursuit over a period of 12 business days. It is assumed that the use of a Portland phone number enhanced the call-back rate, if not the number of people answering the survey.

Gaps related to dates of GR failure, and incentives received, were among details not maintained within in the COP/BES provided data, which became evident after initiating implementation of survey #2. Survey participants enabled completion of some gaps, while others were filled to the best possible degree with researched information found online.

In addition to individual GR report data found on the COP/BES website or posted online via project partners, where possible, sites were evaluated using the 2- and 3-dimension aerial viewing application of Google Earth™ to verify the presence of a GR. This wasn't always effective where buildings had not yet been constructed, or where a variety of smaller GR installations were hidden by trees.   However, the approach was useful in confirming GR removal at four other locations. At other sites, the tool was a significant aid to the confirmation and/or determination of GR failures partially or not reported on the COP/BES list.

Representative Green Roof Data

Portland's list of GR projects is available via public information request from the agency's Bureau of Environmental Services (COP/BES, 2010). A separate list is maintained by the individual who inspects GR installations (personal communications M. Pronold, March 17, 2017). Additional GR information is available at www.portlandoregon.gov/bes/51477.   This website also provides GR project reports and numerous city documents that reinforce the thesis survey findings, while facilitating an understanding of GRs and the unlimited options available for their configuration. Within these resources are data that highlight GRs with failure issues.

Additional web resources accessed for the Portland case study include externally published media reports about Portland GRs and public perception regarding the agency's utility rates and GR funding. A number of these documents provided evidence both of failures among Portland GRs as well as the provision of incentives for GR installations. Wherever possible, these articles were fact-checked with local consultants and agency representatives in an attempt to verify all perspectives involved with reported and un-reported GR issues. Personal communications with Tom Liptan, Portland's GR program creator, were especially beneficial in facilitating the development of a balanced perspective.

GR details provided by the COP/BES and examined for this thesis include:

1. Street address of structure (two addresses were found to have been changed);
2. Type of structure on which the GR has been built (i.e., commercial, institutional);
3. The number of GRs installed;
4. Total square footage of GR (a combined value is provided when more than one GR was installed);
5. GR (re)installation dates (in a single column, even though there are sites that have more than one associated reinstallation date);
6. GR removal dates (in a single column, even though there is more than one date for a handful of sites on the list);
7. Whether or not the GR supplants an array of solar photovoltaic panels;
8. Whether or not the GR is visible from the street; and
9. Type of incentive transaction (including grey to green (G2G), and floor to area ratio (FAR) incentives; completed when studying site reports).

As noted in the list above, counting issues were identified when dealing with the two columns in which the type of GR is defined in one and the dates of installation, (and reinstallation) were noted in the other. Both data sets show comma-separated dates in one cell, rather than two. Periodically, data associated with the second (or third) reinstallation of a GR was missing in these cells. Rows were added to the data set to accommodate reinstallations; column data were added when only one reinstallation was involved.

Additionally, "new," "reroof," and "natural" were undefined types of GRs listed. "New" GRs were assumed to equate to the installation of a GR on new developments. "Reroof" was assumed to reference reinstalled GRs. "Natural," GRs were confirmed via the survey to be passive GRs where no program or customer effort was made to market or install a GR. Instead, natural accumulations of grit supported weeds or mossy growth over time creating unintended stormwater-benefits.

These seemingly trivial distinctions become important when measuring both the types of GRs present historically or currently installed as related to COP/BES outreach efforts, as well as distinguishing between new and reroofed GRs. Care was necessitated relative to the addition of more data lines and columns to the Portland list to accommodate unreported and author-entered findings to avoid double counting of features associated with these GR installations.

Among the counting details added to the list are:

1. Type of use by current occupant (to disaggregate user motivation among groups);
2. Years since the GR was installed or reinstalled;
3. Whether or not the GR was evident on the site via use of Google Earth™; and
4. Subjective assessment (also using Google Earth™) regarding the current value of the GR as a demonstration. This assessment considers whether the GR in question would, or would not encourage passersby to appreciate the GR concept enough to install one of their own, and is based on aesthetics and/or associated signage. The assessment also considers the relative size and location of the GR installed (i.e., Is the GR easily visible from the street? Does it convey that the owner trusts GRs to operate free of leaks? Does it convey that the owner is committed to GRs or the sustainable benefits they are marketed to offer?), and lastly, whether or not the GR was maintained for a minimum level of aesthetics (a detail potentially important to "wanna-be" owners).

Survey Questions – Survey #2

Survey #2 first invited GR owners, managers, or representatives to identify major costs for repairs of roofing membranes and for GRs. The survey also asked (if applicable) how often the GR at the address has been repaired, replaced, and/or removed. Closing questions asked participants to use a four-point Likert scale to rate their personal interest in GRs relative to their experience with the GR at the address and any other GRs with which they have had experience.

The survey also asked respondents to identify their role as the owner, manager, and/or other affiliation for each GR observed. The label choices "contractor" and "owner representative" as were added to the list after survey implementation to accommodate these often-stated titles. Upon confirming a survey participant was effectively affiliated with the GR at each address, details verifying the address of the GR were sought to match it with the COP/BES list.

As noted, one question defined each respondent's value threshold relative to a major roof repair or a major GR failure. The script allowed respondents to frame the value within a list of square foot values (i.e., less than $3/sf; $3–$5/sf; $5–$10/sf, etc.) or from a similar selection of percentage values related to total GR cost. Other than a threshold for costs requiring approval, many participants, especially those who manage, rather than own the GR in question, had no frame of reference with which to choose from either set of values provided to define a major expense. Most participant values were ultimately established by referencing the COP/BES-listed square footage of the GR that the participant managed as a baseline. Reference site records enabled most, but not all respondents, to define their own major repair values.

Using the value derived from this process, or overlooking the value altogether, the next two questions measured the number of major repair events affecting both the roof under the GR (if applicable), and the GR (if applicable). If respondents indicated pursuit of major repairs, the question continued by asking if the GR was ever either removed or reinstalled and, if so, to provide the number of times either had occurred. Although there were only two or three GRs on the entire list with known histories of removal, the purpose of this question was to verify the statistics independent of COP/BES data and media reports via participant accounts of issues encountered. If specific dates of GR removal and reinstallation were included in Portland's list, it would have enabled an even more effective failure analysis. Public media reviews and/or COP/BES project report data did provide some of the missing year information, however.

On all three of the above questions, an option was provided for the respondent to indicate they did not know the answer. Similarly, participants were given the opportunity to indicate that they had pursued a specified number of major roof or GR repairs. Another answer option indicated they had given up on repair of the GR. If they chose the latter, the survey asked if the participant had removed the GR entirely or had simply abandoned the GR in place. For the purpose of agency stormwater retention interests, an abandoned GR is still a functional piece of infrastructure asset that provides more stormwater ecosystem services than a roof without media on it.

The next two questions assessed each respondent's recalled satisfaction with the original GR and an assessment of the current GR using Likert scales ranging from 1 (low) to 5 (high). These same questions also provided an opportunity for participants to respond that they were unfamiliar with the original installation. Ultimately, they also provide the primary measurement data needed to answer the thesis questions regarding the rate of GR failure.

Finally, each respondent was given the opportunity to choose from a range of positive to negative statements that reflected their personal perspective of GRs. Four statements, based upon the premise of a future hypothetical GR purchase, invited respondents to state their perspective given what they had learned about GRs, allowing them to refer to other GRs with which they may have had experience. All prior questions stated, in advance, the need to reference only the GR at the address where each respondent was located.

Data Coding Process – Survey #2

Throughout Survey #2, respondents could make comments regarding the specific GR being discussed. Respondent comments, especially those containing words and phrases regarding issues experienced in the GRs they oversee, were later coded in an MS Excel database following methods established by Hay (2010). Client dissatisfaction, the need for multiple plantings in non-urban agriculture GRs, and abandonment of the GR, are examples of failure included in survey coding. Partial, total, and catastrophic GR failures include lack of or improper GR maintenance, owner-created leaks, normal wear and tear, GR removal to sell or repair the building or its roofing membrane, and any unapproved products and services not covered by warranty.

Among other details, coding allowed confirmation of irrigation and management details sometimes included with COP's original data.

Within respondents' answers to open-ended questions and survey comments, the following variables were highlighted, but only if the variable was mentioned from the perspective of having been a troublesome issue specific to the GR being queried. Respondent mentions of the variables were not included if they were a general reference or noted as a BMP followed by the survey respondent, particularly if the mention was not specific to the GR under discussion. Only after surveys were gathered were the following failure variables added to the data set, all based on respondent references as detailed above:

1. **Customer over commitment** was coded in the same column as **industry/agency overselling** of GR benefits and/or maintenance requirements. This was observed when the survey participant indicated frustration with unanticipated maintenance demands (e.g., for weeding and/or watering) and/or perceived lack of available maintenance guidance.

2. **Planning and engineering failures** resulting in reconstruction of the GR, GR drainage issues and related plant losses, and/or structural failure, regardless of the extent. Comments regarding failures of the planner or engineer to acknowledge safety needs for regular access to the GR were also recorded in this category.

3. **Installation failures** resulting from contractor use of "jerry-rigged" materials, incomplete or inadequate application of specified products, or leaks definitively determined to be caused during GR installation were recorded in this category.

4. **Drainage failures** associated with clogging of GR drain systems (with associated flooding and/or structural leakage) or excessive drainage, including excessive erosion of planting media, were recorded in this category.

5. **Irrigation failures** involving missed irrigations that resulted in plant failures; irrigation systems installed to offset the need for manual water applications; irrigation system failures that resulted in flooding and sometimes structural damage; and frustration expressed by respondents regarding the under-promoted need for irrigation to meet GR growth demands were recorded in this category. Because of its affiliation with GR aesthetics, both this column and the aesthetics column were coded, but only if aesthetics were specifically mentioned in correlation with irrigation failures.

6. Similar to irrigation failures, coding captured respondent complaints about and **mentions of maintenance issues** experienced regarding the GR being surveyed. Specifically, respondents noted frustration with weed management, citing occasions when weed growth overwhelmed them and/or the GR in their ability to: manage the growth (manually and/or with power equipment); remove or treat the weed growth without use of chemical herbicides and/or loss of planting media; or easily dispose of the weed waste created. Because of its affiliation with GR aesthetics, both this column and the aesthetics column were checked, but only if aesthetics were specifically mentioned in correlation with maintenance.

7. Failure related to **lack of maintenance planning** complaints were similar to irrigation complaints, largely based upon respondent perceptions that they had not been adequately warned or prepared with information to deal with the many technical aspects of GR maintenance (i.e., fertility, critical nature of timely weed removal, and the duration of seasonal periods of non-precipitation).

8. **Soil media and planting failures** were combined into one column. Coding captured respondent complaints about and mentions of issues associated with these two components, which are inextricably linked. Where media quality was considered suboptimal (because it came infested with weed seeds, for example), so too was the plant performance. Media that was thought to be deficient in nutrients and/or other necessary but unknown elements was another complaint.

9. **Perceived aesthetic failures** captured the subjective opinions of respective GR owners and property representatives. While the opinions of individuals are known to be subjective, they are still considered important. In particular, individuals who oversee multiple GRs for public agency properties could undermine overall municipal utility intentions and related actions in pursuit of sustainability simply because of their personal aesthetic preferences. This is considered a silo effect that can undermine effective GR maintenance and increase GR removal or abandonment. These outlooks are often capitalized upon by media looking for community issues to report.

10. Perceived **need for refurbishment** of the GR is self-explanatory.

11. **Cost failure** coding recorded owner and manager frustrations predominantly associated with GR maintenance, repairs, and/or refurbishments (if needed). Sometimes it also captured concerns about the cost of the respective GR installation. Where possible, these costs were based upon the "major repair" values determined by each survey respondent at the onset of the survey.

12. **Partial failures** were associated with subjective survey respondent complaints regarding all of the issues listed above. Each time an issue or complaint was registered that was also resolved, it was coded only as a partial failure.

13. **Total failures** tallied either comments provided by the survey participant or were the result of an accumulation of three or more entrenched partial failures, especially if the partial failures resulted in complete reinstallation of the GR.

Coding of responses into categories allowed tallying of results for simplified statistical correlation assessments. A summary of these failures and the survey coding is posted in Appendix C.

Non-Response Coding – Survey #2

Data available or coded for both respondents and non-respondents includes items listed below. In addition to their use as a baseline for the non-response analysis, survey covariates are useful for future statistical analysis.

- ❑ Survey completions (Y/N)
- ❑ Affiliation of contact w/ GR (i.e., resident, employee, realtor)
- ❑ Name of building (sometimes dated/changes misleading/ some sites have similar names)
- ❑ Site location within the City of Portland (not all GRs were affiliated with specific street addresses)
- ❑ Age/type of GR (type = "new," "reroof," or "natural")
- ❑ Date of GR installation and, periodically, date of GR removal/re-installation (these values were originally lumped, and in some cases, were not current)
- ❑ Size of GR (discussion considers GR <1,000 square feet that might (not) be trivial)

- ❑ Location of GR installation on structure (most were evident via Google Earth™)
- ❑ Type of GR owner (i.e., siloed agency, school, bank, bar, apartment, public/private)
- ❑ Type of GR management (i.e., by owner, by contractor, or a combination of both; this information would benefit from additional date associations)
- ❑ Relative health of GR (as evidenced via Google Earth™; *not consistently evident)
- ❑ Incentives from the COP/BES ("Grey to Green" (G2G) and/or "Floor to Area Ratio" (FAR); in some cases, data was not current, leading the author to believe there may be others)

When details regarding a response for any covariate was unidentifiable, "unknown" was the value coded to provide an overview of the entire survey population. In addition to data already available about most GRs (see details regarding Survey #2 Population and Sample), the following data were added to the data set when information became evident or was made available by survey respondents:

- ❑ Years since GR was installed and/or removed
- ❑ Whether or not the GR appeared to be exemplary or trivial based on images provided by Google Earth™. Although subjective, and dependent upon the size and age of the GR (difficult to consistently confirm without reference dates provided by Google), this approach was slow, but easily implemented. From above, GRs are obvious or hidden, and either performing well or not. Other factors influencing the author's subjective categorization included GR age and relative location on the building and in the community. Google Earth™ provides enough clarity of GRs, typically photographed in mid-summer, to determine how well a GR is managed for weeds, with or without aid of irrigation.
- ❑ Known and unknown reasons for non-participation were coded as follows:
    - Unable to locate or to reach any person(s) affiliated with the GR in question.
    - Successfully reached the site's GR affiliate, but the potential survey participant was too busy to participate in the survey.
    - Successfully reached a person affiliated with the GR, but they dislike completing surveys, are not allowed to participate in surveys, or cannot provide survey administrator with contact information for appropriate survey participants.

- Successfully reached a person affiliated with the site, but the person answering indicated the site "no longer has a GR," "never had" a GR, or that the GR has yet to be installed.
- Successfully reached the site's GR affiliate, but the potential survey participant indicated their disinterest in completing the survey because they:
  - don't maintain the GR in question,
  - have abandoned the GR in question, or
  - were "fed up with problems" experienced around the GR in question.

Final Sample Survey #2

GR failure criteria were obtained from 51 surveys of GR owners and managers in Portland, Oregon. From Portland's survey population of nearly 600 GRs a sample of 204 cataloged ICI GRs was surveyed. The author was successful in reaching 108 site representatives (not all of whom were the targeted GR owners or managers), and a total of 55 surveys were completed. This count includes two surveys related to the same location in Chicago (deemed useful as a comparative reference) and two more incomplete surveys that were disqualified either as false starts or a discontinuation of the survey by the respondent before answering all questions. A final response rate of 25.49% was achieved for the 52 surveyed GRs located in Portland from Survey #2.

Among the overlapping categories of respondents were:

- ❑ **8** owners (including those involved with the design, installation, and maintenance of their own GRs);
- ❑ **6** contracted GR professionals directly or indirectly involved with the maintenance of the surveyed GR (2 of these respondents represented one Chicago GR installation kept as a survey reference);
- ❑ **19** site occupants (some of whom were involved with their site's GR planning, installation and maintenance; and

- ❑ **32** owner representatives (includes building managers, building employees, and real estate or externally situated asset managers handling properties that were currently un-owned or the subject of potential sales transactions).

Survey participants stated outright or otherwise demonstrated varied levels of familiarity with their representative GRs. Details include the following survey participant GR affiliations:

- ❑ **27** primarily handled the building's structural and mechanical repairs
- ❑ **34** indicated they managed the plantings of their respective GRs
- ❑ **31** indicated they handled the irrigation of their respective GRs

Limitations - Survey #2

General Survey Limitations. Since participant completion of each survey was actively guided, only one incomplete and one discontinued survey were experienced. Like Survey #1, the distinctions marking GRs as separate from conventional roofs were emphasized by the author/surveyor within the Survey #2 instrument to minimize confounding perceptions among individuals who typically do not differentiate between the roof and the green roof, but rather perceive the two in unison.

Data availability. As noted by Amy Chomowicz, water resource program manager for COP/BES (Maddox, 2015), a research limitation is the current state of GR databases maintained by public agencies. Only periodically do agencies providing incentives for GR installations collect data on GR installations when verifying the installation. When agencies do maintain detailed data beyond the verification, they do not often carry the effort beyond years 1-3 toward a longer-term evaluation of GR effectiveness (personal communications, M. Berkshire, January 19, 2016; A. Chomowicz, January 5, 2016; J. Little, October 26, 2016; J. Harris, December 17, 2015).

Data not always pursued by agencies includes whether or not GRs were installed in pursuit of targeted benefits and whether or not the installations were successful in meeting the owners' and/or the incentivizing agencies' long-term objectives. It also appears uncommon to find data reflecting additional assessment of individual GRs regarding age and type of building, application and frequency of irrigation and maintenance, skills and training of the owner or contractor providing maintenance, GR type installed, relative plant coverage and plant health. Important to this analysis was the length of time between installation of the GRs in question and the dates at which the GR experienced issues or failures (if applicable). Although the absence of these data is a potential limitation that can be overcome, it is worth mentioning as a useful tool for measuring post-installation activities.

GR data required of owners by public agencies typically includes information regarding current owners and managers of every GR installation, which eventually changes over time. Finding individuals who can speak to the status of particular GRs was sometimes difficult, if not impossible. This was especially true where multiple GR installations are managed by one branch of an agency (e.g., parks departments or school districts whose sites are internally maintained by a pool of employees). It was also true where a GR installation is an insignificant element of a much larger real estate holding, especially if the building was currently on the market and/or contractually managed. This situation is not helped by the fact that many of these GRs are either deemed "self-sustaining" by their principal owner (as per survey communications with Portland Parks and Public Schools representatives), or abandoned for lack of an invested owner (personal communications, K. Arcaro, August 9, 2016). These properties are not likely to have staff available to actively participate in surveys like the ones implemented for this thesis.

Non-Response Analysis – Survey #2

The process of non-response bias (NRB) analysis for this thesis considered why nearly 47% of the potential survey population among Portland's 204 ICI GRs did not participate in completion of Survey #2. NRB analysis can highlight particular data as predictors of survey participation, as well as the positive or negative outcome of related but non-surveyed responses. Lack of NRB consideration prior to survey development and implementation (as was the case for this survey), "…can lead to sample selection bias even if non-respondents are similar to respondents in observable characteristics but differ in their [interest in the environment, GRs, and/or sustainable infrastructure] due to unobservable characteristics*"* (Whitehead et al., 1993, as per Mitchel & Carson, 1989).

Despite this lack, the NRB analysis objective aims to determine if the Survey #2 sample is representative of the Portland sample population and the larger population of municipal GR programs in North America. To meet this objective, comparisons were made between respondents and non-respondents by count; building type; size of GR(s) installed; incentives received; site closure, GR removal, or reinstallation data; and subjective visual assessments. The following discussions and tables provide an overview of findings in each of these areas.

Count of Survey #2 Responses and Non-Respondents by Year. Of the 204 Portland ICI GRs listed by COP/BES that were sought for participation in Survey #2, there were 93 non-respondents (46.27% of the total population count; equivalent to a 39.46 average annual rate of non-response). Table 12 summarizes the relative counts of Survey #2 respondents to non-respondents in each year. The findings confirm a 25.8% rate of participation after reaching 108 (53.7%) of Portland's ICI GR owners, managers, or asset representatives and completing surveys with 52 of them.

Table 12.
Non-Response Analysis of Portland Green Roofs by Year and Response Count

YEAR GR Installed	# GRs Installed by Year	# of Contacts Reached and/or Surveyed	# of Contacts Surveyed	# of Contacts NOT Reached and/or Surveyed	% of Non-Response by Year
1986 +/-	**1**	**1**	**1**	**0**	**0%**
1998	**1**	**1**	**0**	**0**	**0%**
1999	**1**	**1**	**1**	**0**	**0%**
2000	**2**	**0**	**0**	**2**	**100%**
2001	**3**	**2**	**2**	**1**	**33%**
2002	**5**	**3**	**2**	**1**	**17%**
2003	**8**	**3**	**1**	**4**	**57%**
2004	**5**	**1**	**1**	**4**	**80%**
2005 (1)	**10**	**6**	**2**	**4**	**40%**
2006	**9**	**4**	**1**	**4**	**50%**
2007	**11**	**5**	**3**	**6**	**55%**
2008	**17**	**8**	**3**	**10**	**59%**
2009 (1)	**20**	**10**	**5**	**11**	**58%**
2010	**23**	**11**	**4**	**12**	**55%**
2011	**19**	**11**	**6**	**7**	**39%**
2012	**17**	**14**	**7**	**3**	**18%**
2013	**24**	**11**	**6**	**13**	**54%**
2014	**12**	**7**	**3**	**5**	**42%**
2015	**6**	**4**	**2**	**2**	**33%**
2016	**1**	**1**	**1**	**0**	**0%**
Unknown Yr. (1)	**9**	**6**	**1**	**4**	**40%**
TOTALS:	204	106	52	93	39%

(1) Counts do not include 2 disqualified and 2 Chicago GR surveys

Non-respondent analysis by building types. There is value in considering the survey non-response rate among various types of COP/BES listed GRs since some categories had consistently high rates. Among these are non-responses from municipal utility sectors that manage several sites, especially where GR installations are small, overall, and/or were said to be minimally or passively maintained (personal communication, M. Sorensen, August 23, 2016). GRs installed on properties managed by COP parks, schools and stormwater management groups may exemplify siloed communications, limited funds, and/or differing levels of internal support for GRs, both within the sector, and between agency sectors.

One COP Public Schools GR representative reached suggested it is counterintuitive to think that schools and parks are good locations to demonstrate GRs and/or environmental sustainability (personal communications, N. Bond, August 19, 2016). These “legacy” GR installations are thought to suffer high rates of failure due to lack of qualified, financed, and committed volunteers to maintain them once parents, students and teachers move on. No additional surveys were obtained despite repeated attempts to reach site specific COP Public Schools representatives. Lack of data therefore limits associated findings.

Tables 13 and 14 summarize counts of Survey #2 respondents and non-respondents in terms of the respondent’s building type, as listed by COP/BES. This analysis confirms the implied COP/BES GR failure definition. Also relevant is the potential count of incentives discovered in the midst of the thesis research, either unrecorded, or in association with undocumented GR sites. Tables 13 and 14 also illustrate that no survey participation was gained from GR owners, managers, or their representatives in the standard apartments, grocery, and open-space sectors of the total population. This may reflect that the predominantly small GRs at these sites are a low priority, especially among staff members who are difficult to identify and/or contact for survey implementation.

Table 13.

Response Analysis of Portland Green Roof Incentive Recipients by Building Type

CATEGORIES of Green Roof Building Uses (segregated by target markets)	**Consolidated Categories**	**Survey Sample** (n = 53)	**% Survey Respondents from Sample**	**Surveyed Count of Incentives Rcvd**[1,2]	**Potential # of Un-Recorded Incentives**
Commercial - General: (3.5% Population)	Personal Health	2	4%	2	1
	Social NGOs	1	2%	0	0
	Finance (1 NGO)	2	4%	3	3
	Parking and Transit	2	4%	1	0
		7	**13%**	**6**	**4**
Commercial - Residential: (6.9% Population)	Affordable and Student Housing	8	15%	8	1
	Standard Apts	0	0%	0	0
	High-Efficiency Apts/ 1 Luxury Hotel	6	11%	5	1
		14	**26%**	**13**	**2**
Commercial - Retail: (4.5% Population)	Food and Beverage	3	6%	2	0
	General	3	6%	1	0
	Grocery	0	0%	0	0
	Mixed Use/Offices	3	6%	2	1
		9	**17%**	**43**	**1**
Industrial (0.9% Population)	Manufacturing	3	6%	3	1
	Warehouse	1	2%	1	0
		4	**8%**	**4**	**1**
Institutional (8.9% Population)	Religious/Education	8	15%	6	1
	Public Infrastructure	6	11%	5	1
	Medical	2	4%	2	0
	Mixed Use/Offices	2	4%	1	1
	Open Space/Parks	0	0%	0	0
		18	**34%**	**14**	**3**
TOTALS:	T + % values skewed by 2 reinstallations	**52**	**98%**	**80**	**11**

1) Original data provided confirming actual count of incentives is underreported, or periodically vaguely detailed (i.e., "Y" for type of defined incentives received). Evidence of incentives provided was discovered for at least
11 sites in public/online media.

2) Coded types of Incentives included: (0)=No Incentive; (1)=G2G; (2)=FAR; (3)=both.

Table 14.
Non-Response Analysis of Portland Green Roof Incentive Recipients by Building Type

CATEGORIES of Green Roof Building Uses (segregated by target markets)	**Consolidated Categories**	**Total Population** (n = 202)	**Non Response % of Sample**	**Non-Surveyed Counts(3) of Incentives(1,2) Rcvd**	**Potential # of Un-Recorded Incentives**
Commercial - General: (6.4% of Pop)	Personal Health	4	25.0%	1	0
	Social NGOs	3	33.3%	1	0
	Finance (1 NGO)	3	33.3%	1	0
	Parking and Transit	3	33.3%	1	0
		13	**30.8%**	**4**	**0**
Commercial - Residential: (28% of Pop)	Affordable and Student Housing	11	18.2%	2	0
	Standard Apts	11	54.5%	6	2
	High-Efficiency Apts/Luxury Htl	35	60.0%	21	0
		57	**50.9%**	**29**	**2**
Commercial - Retail: (17% of Pop)	Food & Bev	10	50.0%	5	0
	General	10	50.0%	5	0
	Grocery	5	60.0%	3	0
	Mixed Use/Offcs	9	55.6%	5	1
		34	**52.9%**	**18**	**5**
Industrial (3.5% of Pop)	Manufacturing	6	33.3%	2	1
	Warehouse	1	0.0%	0	0
		7	**28.6%**	**2**	**1**
Institutional (45% of Pop)	Religious/Edct'n	40	40.0%	16	0
	Public Infrastr	27	40.7%	11	1
	Medical	12	41.7%	5	0
	Mixed Use/Offcs	5	40.0%	2	0
	Open Spc/Parks	7	28.6%	2	0
		91	**39.6%**	**36**	**1**
TOTALS:		**202**	**42.1%**	**85**	**7**

1) Original data provided confirming actual count of incentive is underreported, or periodically vaguely detailed (i.e., "Y" for type of defined incentives received). Evidence of incentives provided was discovered for at least 11 sites in public/online media.
2) Coded types of Incentives included: (0)=No Incentive; (1)=G2G; (2)=FAR; (3)=both.
3) Duplication of category count is possible in this category; in particular, re-installed sites have records of past issues; other sites appear marginal, or small and marginally beneficial to public PR.

Response Analysis via Building Size

Tables 15 and 16 summarize Survey #2 responses relative to COP/BES data listing GR building size. Association of GR failure with building size would be a next logical step, but was not pursued for the thesis analysis.

Table 15.
Response Analysis of Portland Green Roof Incentive Recipients by Building Size

CATEGORIES of Green Roof Building Uses (segregated by target mkts)	**Consolidated Categories**	**Survey Sample** (n = 53)	**% Survey Respondnts from Sample**	**Surveyed Counts of Incentives Rcvd[1,2]**	**Potntl # of Un-Recorded Surveyed Incentives**
Building Size	< =200 sq ft	6	11%	2	1
	201-1000 sq ft	10	19%	7	1
	1,001 - 5,000 sq ft	20	37%	15	1
	5,001 - 10,000 sq ft	7	13%	4	1
	10,001 - 20,000 sq ft	8	15%	4	0
	> 20,000 sq ft	3	6%	3	0
	Value skewed (2 reinstalls)[3] —>	**54**	**100%**	**35**	**4**

Table 16.
Non-Response Analysis of Portland Green Roof Incentive Recipients by Building Size

CATEGORIES of Green Roof Building Uses (segregated by target mkts)	**Consolidated Categories**	**Total Pop** (n = 202)	**% Non Response from Sample**	**Non-Surveyed Counts[3] of Incentives Rcvd[1,2]**	**Potntl # of Un-Recorded Non-Svy'd Incentives**
Building Size	< =200 sq ft	31	41.9%	13	
	201-1000 sq ft	52	36.5%	19	
	1,001 - 5,000 sq ft	64	42.2%	27	
	5,001 - 10,000 sq ft	23	47.8%	11	
	10,001 - 20,000 sq ft	22	45.5%	10	
	> 20,000 sq ft	12	58.3%	7	
		202	**46.0%**	**93**	**?**

1) Original data provided confirming actual count of incentive is under-reported, or periodically vaguely detailed (i.e., "Y" for type of defined incentives received). Evidence of incentives provided was discovered for at least 11 sites in public/on-line media.

2) Coded Types of Incentives included: (0)=No Incentive; (1)=G2G; (2)=FAR; (3)=both.

3) Duplication of category count possible in this category; particularly re-installed sites have record of past issues; other sites appear marginal, or small and marginally beneficial to public PR.

Response Analysis via Type of Green Roof Listed

Tables 17 and 18, summarize Survey #2 responses relative to COP/BES GR data listing the type of GR installed. Relevant to the analysis are natural GRs, which can provide subjectively perceived high-quality aesthetics as a result of natural progression. They also provide utility agencies with stormwater management benefits without program costs. Natural GRs are counted in COP/BES data despite lack of incentive program participation from owners of these unmaintained structures. Whether or not, owners (and neighbors) consider these installations to be problematic or successful would require a separate study.

An association between the rate of failure and the type of GR would also be a next logical step in this analysis. The average length of time before appearance of GR and/or roof issues was calculated to be 5.96 years. This is considered a standard "refurbishment" period for GR plants and media among GR consultants (personal communications, J. Crumrine, March 2, 2017).

Table 17.
Response Analysis of Portland Green Roof Incentive Recipients by Type of Green Roof

CATEGORIES of Green Roof Building Uses (segregated by target mkts)	**Consolidated Categories**	**Survey Sample** (n = 53)	**% Survey Respondents from Sample**	**Surveyed Counts of Incentives Rcvd**[1,2]	**Potntl # of Un-Recorded Non-Svy'd Incentives**
Type of Green Roof (Urban Ag count is separate from others)	Urban Agriculture	3	6%	1	
	New	35	65%	27	2
	Reroof	18	33%	12	2
	Natural	1	2%	0	Y
	Values skewed (2 reinstalls)[3]	**54**	**100%**	**39**	**4+**

Table 18.
Non-Response Analysis of Portland Green Roof Incentive Recipients by Type of Green Roof

CATEGORIES of Green Roof Building Uses (segregated by target mkts)	Consolidated Categories	Total Population (n = 202)	% Non-Response from Sample	Non-Surveyed Counts[3] of Incentives Rcvd[1,2]	Potntl # of Un-Recorded Non-Svy'd Incentives
Type of Green Roof (Urban Ag count is separate from others)	Urban Agriculture	4	0%	0	0
	New	148	77.7%	115	2
	Reroof	49	63.3%	31	?
	Natural	5	0.0%	0	Y
		202	**72.3%**	**146**	**2+**

1) Original data provided confirming actual count of incentive is underreported, or vaguely detailed (i.e., "Y" for type of incentives received). Evidence of incentives provided was discovered for 11 sites in public media.

2) Coded types of Incentives included: (0)=No Incentive; (1)=G2G; (2)=FAR; (3)= both.

3) Counts highlight instances where an unidentified incentive has been provided.

Response Analysis via Incentives Received

Tables 19 and 20 summarize Survey #2 responses relative to COP/BES GR data listing GRs that received agency Grey to Green (G2G), and/or Floor to Area Ratio (FAR) incentives. ICI GRs listed by COP/BES included at least eight sites with unknown funding sources discerned via online media and COP/BES project report references. Careful tracking of the funding associated with all GR installations, even if they qualify as "experiments," makes transparent all incentive program activities.

Table 19.
Response Analysis of Portland Green Roof Incentives by Count of Incentives Received

CATEGORIES of Green Roof Building Uses (segregated by target mkts)	**Consolidated Categories**	**Survey Sample** (n = 53)	**% Survey Respondents from Sample**	**Surveyed Counts of Incentives Rcvd**[1,2]	**Potntl # of Un-Recorded Non-Svy'd Incentives**
Use of COP/BES Incentive(s) (Total Sample) n=53	None, or Unidentified	15	28%	0	Y
	Other Incntvs ID'd [1, 3]	3	6%	3	3
	G2G (Grey to Green)[1, 3]	34	64%	33	1
	FAR (Floor to Area Ratio)[2]	1	2%	1	0
	Both Incentives	1	2%	1	0
	Values skewed (2 reinstalls)[4]	**54**	**102%**	**38**	**4+**

Table 20.
Non-Response Analysis of Portland Green Roof Incentives by Count of Incentives Received

CATEGORIES of Green Roof Building Uses (segregated by target mkts)	**Consolidated Categories**	**Total Population** (n = 202)	**% Non-Response from Sample**	**Non-Surveyed Counts**[3] **of Incentives Rcvd**[1,2]	**Pot # of Un-Recorded Non-Svy'd Incentives**
Use of COP/BES Incentive(s) (Total Population) n= 135	None, or Unidentified	75	0.0%	0	Y
	Other Incntvs ID'd [1, 3]	12	16.7%	2	12
	G2G (Grey to Green)[1, 3]	105	66.7%	70	1
	FAR (Floor Area Ratio)[2]	6	83.3%	5	0
	Both Incentives	6	83.3%	5	0
	Values skewed (2 reinstalls)[4]	**204**	**40.2%**	**82**	**13+**

1) Original data provided confirming actual count of incentive is underreported, or vaguely detailed (i.e., "Y" for type of incentives received). Evidence of incentives provided was discovered for 11 sites in public media.

2) Coded types of Incentives included: (0)=No Incentive; (1)=G2G; (2)=FAR; (3)= both.

3) Counts highlight instances where an unidentified incentive has been provided.

4) Duplication of category count is possible in this category; in particular, reinstalled sites have records of past issues; other sites appear marginal, or small and marginally beneficial to public PR.

Size and Quality of GR vs. Incentive PR

Examples of GRs that subjectively qualified as trivial included at least 53 installations (equivalent to 26% of the total count) among all 78 of the ICI GRs listed in Portland that are sized under 1,000 square feet. These GRS were clearly unmanaged (rampantly weedy) and were situated where people can easily see them. Bike shelters are a common application of small GR demonstrations that tend to go unmanaged, which were noted to require significant amounts of up-front funding to install by their affiliated representative(s). This issue may be tangential to NRB analysis, but suggests agency policy would benefit from minimum standards for approval of incentive funding. In some cases, these GRs may have a negative effect on public perception from both an aesthetic perspective and, more importantly, from use of public funds to install them. Of the 204 GRs on the list, the following overlapping counts were discerned among the 78 GRs sized under 1,000 square feet:

- ❑ 5 small (< 1,000 square feet; equivalent to 2.5%) but effective demonstrations of functionally relevant GRs. These sites were clearly positioned in public venues, maintained, and provided educational signage that covered most of the why's and how's of GR planning and installation.

- ❑ 31 (15%) of small GRs indicated minimal owner commitment. These GRs may receive maintenance, but are installed on structures that don't require a leak-free experience, such as on buildings and garages where leaks are less problematic, if they do occur. For the ROI to the utility agency, these GRs may not pass scrutiny.

- ❑ 54 (26%) the smallest of Portland GRs (under 100 square feet in size) indicated to the thesis author a lack of commitment in terms of location (on structures that don't require leak-free performance), especially in out-of-the-way locations, and/or which showed an obvious lack of maintenance.

Assessing Green Roof Promotional and Demonstration Values

This assessment was enabled by use of Google Earth™, and sometimes via drive-by or on-site tour by the thesis author. It was pursued to determine whether Portland's GRs provide positive or negative promotional value. Specific sites were identified where the GRs were relatively tiny, hidden from public access, demonstrated a lack of needed owner maintenance, and/or portrayed a lack of owner faith in the membrane-protecting benefit that GRs are promoted to provide. These "demonstration" GRs are typically installed on outbuildings where failures would not pose significant problems to the structure or its contents if leaks occurred. This issue highlights the conundrum of promoting new and untested technologies that have yet to achieve freedom from failures.

Whether or not the size of the GR and its placement make it worthy of a rate-payer financed incentive deserves consideration. Figure 16 highlights a GR installation that was awarded a G2G incentive. The author subjectively interpreted this as a trivial GR, in part because it conveys only partial commitment to GR technology, and somewhat suggests that leaks happen.

Figure 16. Portland, Oregon, recipient of green roof incentive.

As noted in Tables 21 and 22, Google Earth™ was used to examine every GR on the COP/BES list to: 1) verify a GR had been installed or still existed; 2) verify the size of the GR relative to the data provided by COP/BES; 3) determine where the GR(s) was located relative to the overall structure (e.g., on the primary structure or on structures where waterproof functions are not mandatory); and 4) assess the relative appearance of the GR (e.g., dormant, green, eroded, patchy/discolored, presence of unmaintained [in particular, tall] weeds, etc.).

The clarity of Google Earth images, and the ability to see GR installations both from above and from lower angles during the hottest summer months, exemplifies how this approach might be applied if GRs were to be evaluated post-installation without the benefit of on-site examinations. One drawback is that Google Earth images are not visually date-stamped, and on three occasions noted, the image was clearly captured before a GR was installed. Another drawback is evident with respect older and/or smaller GR installations located in forested areas: many of these GRs are difficult, if not impossible, to see from aerial perspectives. They are alternately evident from the ground-plane perspectives offered by Google Earth, but only if the site is located near a roadway where street-level images are gathered.

Table 21.
Response Analysis of Green Roof Incentive Recipients by PR/Demonstration Value

CATEGORIES of Green Roof Building Features	Consolidated Categories	Survey Sample (n = 53)	% Survey Respondnts from Sample	Surveyed Counts of Incentives Rcvd[1,2]	Potntl # of Un-Recorded Non-Svy'd Incentives
Real Estate	Property on the Mkt	0	-	0	Y
Negative Pgm PR	Abandoned/No Maintenance	6	11%	4	Y
Not as Listed by COP/BES	No GR is Present	0	-	0	N
Subjective Visual GR Assessment[5]	Good Demo/PR	24	44%	13	2
	Small and/or Trivial[4] 25-44T (coded "1")	12	23%	8	0
	Trivial/Negative GR PR[4]; (coded >1)	7	13%	5	2
	Unknown/Worth Evaluation	0	0	0	0

Table 22.
Non-Response Analysis of Green Roof Incentive Recipients by Building PR/Demonstration Value

CATEGORIES of Green Roof Building Uses (segregated by target mkts)	Consolidated Categories	Total Population (n = 202)	% Non Response from Sample	Non-Surveyed Counts[3] of Incentives Rcvd[1,2]	Pot # of Un-Recorded Non-Svy Incentives
Subjective Visual GR Assessment (using Google Earth™ + ease of public viewing)[5]	Good Demo	88	43.2%	38	Y
	Small / Trivial[4] (coded 1)	43	20.9%	9	Y
	Trivial/Negative PR[4]; (coded >1)	43	41.9%	18	Y
	Unknown/Worth Evaluating	10	0	0	Y

1) Original data provided confirming actual count of incentives is underreported, or vaguely detailed (i.e., "Y" for type of incentives received). Evidence of incentives provided was discovered for 11 sites in public media.
2) Coded types of Incentives included: (0)=No Incentive; (1)=G2G; (2)=FAR; (3)= both.
3) Highlights instances where an unidentified incentive has been provided.
4) Indicates that evidence of incentives provided was discovered for 11 sites in public media.
5) Public ease of viewing includes ability to see GR from street or from surrounding buildings.

Summary of Non-Response Analysis

Thesis survey participation rates may be considered low relative to decades-old industry standards, as posited by Cook, Heath, and Thompson in 2000 and by Johnson and Owen in 2008. Response rates between 35% and 53% percent were the standard at those times, but response rates have since been consistently reported to be in decline. Initial lack of direct contact information of survey participants was elemental to this limitation.

The thesis author has speculated that individuals involved with successful pursuit of incentives may be layers apart from access by survey administrators. Particularly if the real estate on which the GR is situated has been sold or management of the GR has been handled by more than one individual and/or firm over the lifetime of the GR or the building, finding an interested and available individual with knowledge about the specific project may be difficult or impossible.

Whether or not a GR owner, manager, or representative (if one was successfully contacted to participate in the survey) is correct about the success or failure status of their GR, survey non-participants who may have considered their installations to have failed may also have chosen not to participate in the survey for various reasons. For example, the uninvolved survey participant might fear repercussions from their supervisors and/or colleagues, who may perceive them to be personally deficient or conspicuous because of their affiliation with the respective GR failures. Others may want to avoid publicity of the condition of their GRs, or just be disinterested.

Differences that are evident among owners and managers of mostly small GRS in open spaces may bias the sample data. Specifically, a lack of survey participation from schools, parks, and high-end condo representatives was limited by access to survey participants, and/or respondent interest in survey participation. Although greater participation in Survey #2 would have been ideal in the interest of confirming the thesis hypotheses, the 52 responses obtained are statistically sufficient among a majority of Portland's GR owner types to provide representative insights.

Owner and Manager Measures of GR Failure

After coding survey data following methods established by Hay (Hay, 2010), MS Excel sorting and use of pivot tables enabled counting of Survey #2 results. In addition to obtaining an understanding of each respondent's cost-related definition of "major failure" (associated with the per square foot cost to repair their roof or GR), survey interviews noted respondent comments about their specific GRs.

Counts of coded GR issues mentioned by respondents. Survey #2 did not ask specific (leading) questions regarding GR irrigation, maintenance, or failures of the GR that each respondent owned, managed, or represented. Instead, respondent answers were coded to highlight issues they mentioned during the survey. Specifics recorded included any mention of: 1) a respondent's horticulture familiarity; 2) whether or not irrigation and/or maintenance is regularly provided, or was ever provided to the GR with which they are affiliated; and 3) any GR-related issues or concerns mentioned during the telephone survey mentioned with any survey question. The concerns were also coded when the comment expressed dissatisfaction or failure with their particular GR, and did not include general statements of a respondent's knowledge about an issue or about GR needs or BMPS.

Table 23 ranks and summarizes the count of coded survey responses mentioned by Survey #2 respondents, as described above. The count of issues enables a preliminary measure of failures types noted. Coded variables used include "n/a" (not a failure), partial failure, and total failure among all 55 GRs sites surveyed, and includes data gathered from managers of two Chicago GR sites. "Y" = Yes; "N" = No; "Y/N" indicates that the survey participant provided both

Table 23.

Survey #2 Summary of Coded Perceptions of Failure by 55 Portland Green Roof Owners, Managers, or Representatives

Respondent's Green Roof Need Specified and/or Failure Mentioned	**Responses and Count of Responses**	**Type of Failure Associated w/ Respondents' Responses**
Respondent's GR Is Maintained	34: Y 5:Y/N 11: "N"	Partial Failure
Respondent's GR Is Irrigated	27:Y 16:Y/N (2Fails) 10:N (2F)	Partial Failure
Perceived Aesthetic Failure	22 Total 4:"?"; 8: "Perspective"	Partial Failure
GR "Needs to Be Refurbished"	20 Total (3 respondents uncertain)	Partial - Total
Timely Maintenance Failures	20 Total; (5 respondents uncertain)	Partial - Total
Media and/or Planting Failed	19 Total 3:"?"; 2: "Perspective"	Partial - Total
Failure re: GR Planning/Engineering (general)	16 Total	n/a
Timely Irrigation Failures	14 Total; 4:"?"	Partial - Total
Cost Overrun Failures	13 Total (8 respondents uncertain)	Partial
Marketing Oversell re: GR Maintenance Requirements	12 Total	Partial
Failure re: Improper Installation	10 Total; 5 re: Membrane	Partial - Total
Failure re: GR Planning/Engineering (re: safety)	5	Partial
Failure re: Poor/No GR Drainage	4	Partial (Major) - Total
Marketing Oversell re: GR Summer Irrigation Requirements	3	Partial
Respondent Appears to be Horticulturally Intuitive	3	n/a
Marketing Oversell re: GR Seasonal Aesthetics	2	Partial
Failure re: GR Planning/Engineering (plant layouts mentioned)	2	Not a Failure
Failure Related to Planning or Engineering of GR (soil media)	1	Partial - Total

responses and suggests inconsistent or purposefully changed application of GR treatments over time. “Perspective” and “?” indicate that the respondent’s perspective about the issue was uncertain and/or was considered by them to fall outside of the social norm of people who value green and tidy GRs. Values associated with each count are shown in parentheses. Analysis includes the following results:

Perceived aesthetic failure. (22 total comments; first ranked issue). These comments noted respondent frustration when the GR didn’t meet their aesthetic expectations. This valuation is the respondent’s subjective opinion, noting if respondent was open to a naturalized GR effect rather than expecting a uniform green carpet of plants.

GR needed to be refurbished. (20 total comments; second ranked issue). The category is self-explanatory. Two separate survey questions also asked whether or not a major repair of the roof or the GR had been made within the first five years of GR installation. The results of these questions follow, and illustrate definitive owner/manager awareness of the distinctions between repairs and refurbishment, and that GR repairs are required slightly less often than roof repairs, but generally when a roof repair is pursued. See Appendix C for graphic summaries of responses to these particular questions, along with respondent comments.

Among the people answering the “count of major repairs within five years” question relative to the roof (separate from the GR), six of 53 respondents (11. 3%) indicated one major repair was needed, two more indicated two repairs had been required within five years of GR installation, and three more (half of 1%) indicated more than four major roof repairs had been needed. Three respondents did not know the history of their buildings’ roof repairs. Overall, slightly more than 75% of respondents needed no major roof repairs within the first 5 years of installing a GR.

The count of GRs needing major repairs was similar to the count of roofs needing major repairs, but ultimately fewer GR repairs were needed than roof repairs. Among the people answering the "count of major repairs within five years" question relative to the GR (separate from the roof), five of 53 respondents indicated the need for 1 major repair (9.4%), and one more indicated the need for 2 major repairs. Among these, three abandoned their GR, and one more noted that the GR was entirely removed. Of the GRs needing major repairs, only one was reinstalled. Two more respondents were not familiar with the repair histories of their GR. Overall, 83% of respondents (44 out of 53) required no major GR repairs.

Is the GR maintained? Timely maintenance failures noted. (34 GRs are maintained, 20 failures were cited; maintenance is the third ranked issue). Confirmation was sought to complete limited COP/BES data indicating whether a site's GR was owner- or contractor-maintained via unsolicited comments provided by survey respondents. If the question of maintenance and by whom it is provided remains unclear is noted in "Y/N" answers in Table 23.

Among the 50 people with active involvement or affiliation with a surveyed GR, 34 indicated they had maintenance issues resulting in a partial or total GR failure. Five respondents (real estate and asset management officers and owner representatives) didn't know if the GR was maintained or never revealed in their comments the level of GR maintenance provided. Eleven more respondents currently provided little to no maintenance to their GRs. The word "currently" is critical, since maintenance is understood by most people in the GR industry to be required following the installation of any GR, until the GR is fully established over a period of one to three years.

Respondent comments about maintenance failures included references to lack of GR maintenance (such as missed weeding opportunities, often related to GRs situated out of sight) and/or maintenance failures (one requiring a complete reinstallation of GR plants due to weed invasion). 68% of respondents mentioned *maintenance failures in general*, making this the most common GR failure issue cited. More specifically, *need for timely maintenance* was the third most cited issue.

Media/planting failures. (19 total comments; fourth ranked issue). These comments referenced failure issues that would be impossible to fully appreciate unless on site to consider numerous potential contributing factors. In most cases, respondents referenced the need to refurbish the GR, or to reinstall plants because the original and other installations had not fully taken root, or had not provided the intended coverage.

Planning and/or engineering failures. (16 total comments; fifth ranked issue). Unique comments were noted on 16 occasions specific to GR planning and/or engineering. Five comments related to a lack of GR designer/planner awareness regarding specific safety measures to access the respondent's GR, if not also training to safely access the GR while carrying or using GR products and maintenance equipment. Five other comments were associated with short-term "partial" failures that resulted from incomplete installations addressed by warranties. Two respondents commented on the non-failure need to provide extra maintenance to keep the originally designed plant layout within a particular pattern for viewing by people inside the building.

Is the GR irrigated? Timely irrigation failures noted. (14 failures cited; sixth ranked issue). This category noted comments that confirmed installation of GR irrigation systems. From a total of 52 Portland respondents, 27 respondents (52%) indicated their GR included an irrigation system of some kind; 10 more (19%) indicated no irrigation system was ever installed.

At a 53% rate of respondent mention, irrigation failures, *in general*, were the second most common issue cited. More specifically, timely irrigation was the seventh most cited issue. Among 17 respondents indicating they had issues associated with the need for irrigation, or with complete irrigation system failures, two were noted as major GR failures. Among the 10 respondents indicating no irrigation system was installed, there were another two major GR failures noted. Comments often cited GRs situated out of sight as the reason necessary irrigation was missed, which led to plant decline and/or losses.

Cost failures. (13 total comments; seventh ranked issue). This category noted respondent references to unanticipated GR costs, either overall or those associated with failed aspects. Any GR replaced was counted in this category. A portion of the survey was dedicated to consideration of what constitutes the value of a major repair cost, as illustrated in Figure 17. Respondents provided their perspectives as it relates to "the industry's average cost of '$15-$20 per square foot for all types' of GR installations" and as it related to their specific GR. Providing respondents with these reference areas allowed them to be more specific about the costs they have incurred managing and/or repairing their respective GRs.

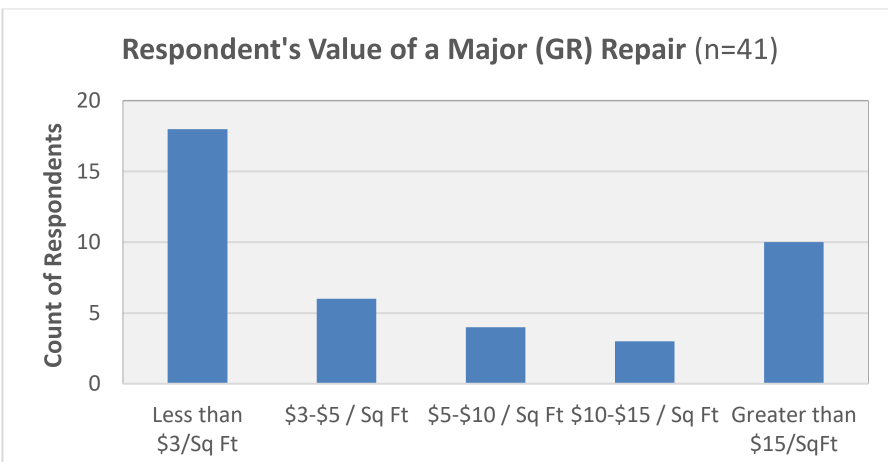


Figure 17. Respondent Values Defining a "Major" Expense

Marketing of GR benefits. (12 comments overall; eighth ranked issue). Although experts and owners apparently perceive a low association between marketing and GR failure, this issue was coded in 16 unique mentions by survey respondents. In particular, horticulturally limited GR owner, manager and representative respondents to Survey #2 indicated concerns related to being oversold on the commitments required of them to manage their respective GRs. Alternately, some respondents retrospectively indicated that they were overconfident in their ability to avoid failure relative to weed management and irrigation on a consistent and timely basis. In general, respondents indicated having been encouraged to over-commit, and/or who mentioned unrealized expectations in three areas, are summarized as follows:

- **Maintenance**: As noted above, maintenance was the most cited issue, especially among the majority of owners who are not horticulturally inclined. Overall, 12 respondents cited that a lack of maintenance information was provided with their GR installation, or that they didn't know where to find it on their own.

- **Irrigation**: Three respondents were told they could do without irrigation but eventually installed systems to manage plant survival during Portland's extended summer and periodically extended heat spells. Particularly where the GR is not visible, lack of an automated irrigation systems was a failure-aggravating issue.

- **Aesthetics**: Two individuals assumed the GR would look good year-round, or stated that they were not aware of potential visual chaos that would/did occur, even if it was due to plant dormancy, or more understandably, a lack of weeding (and therefore the owner's responsibility).

Installation failures. (10 total comments; ninth ranked issue). These respondent comments generally concern specifications not followed by GR installers and included failures addressed by warranties, including ineffective membranes or flashing (five comments specified these issues), and, once, the provision of root-bound plants that later died (buyer beware!).

Drainage failures. (4 total comments; 10th ranked issue). Comments here either referenced drainage concerns, or confirmed major GR drainage failures.

Willingness to Pay for a Green Roof. A four-tiered Likert scale was used among GR owners and managers to determine their hypothetical WTP for, or alternately, avoid another GR in the future. The results are listed in Table 24 and illustrate that 47.2% of survey respondents would pursue another GR, but completion of their purchases would depend upon the outcome of details related to the history of the structure and other risks. Another 40% of survey respondents would hypothetically seek out or add a GR to a future building because they strongly value GR technology. On the other end of the scale, 13.2 % of respondents were less than likely to pursue a GR because of the risks involved, and nearly 4% would avoid the purchase or installation of any form of GR. This would be a valuable question to ask among GR owners in different municipalities, and would help verify whether or not Portland, Oregon is, in one or more ways, representative of other communities providing GR incentives.

Table 24.
Survey Respondents' Future Interest in a Green Roof

Answer Options	Response Percent	Response Count
• "I greatly value green roofs, and would seek them out in future building purchases, or add them to buildings I own."	39.6%	21
• **"Depending upon the history of the green roof, and other risks, I might purchase a building with a green roof."**	**47.2%**	**25**
• "Due to the risk and/or expenses, I am less than likely to purchase a building with a green roof, or seek out a building that includes a green roof."	13.2%	7
• "I would absolutely not buy a building with a GR/I would never install one."	3.8%	2

This survey measure also highlights, indirectly, two important findings relative to the marketing of GRs. First, the results reveal that agency GR representatives are consistently willing to tolerate or otherwise "pay whatever is necessary for repair of GR failures." (personal communications, K. Christoph, August 30, 2016). Often, the budget for these GRs is handled by another siloed agency division. None of these GRs indicated failure issues were ever present. On the other hand, GR owners and managers whose budgets were limited or otherwise under their direct authority were consistently conservative with their commitment to spend no more on repairs than 50% of the value of the existing GR with which their survey was affiliated.

The second finding associated with this question is that GR survey participants who are older and familiar with the costs of GR installation and management expressed dissatisfaction with safe access to, and/or maintenance of their GRs, to the degree of complete dismissal of a future GR. This point is important given the aging population of baby boomers in Portland, throughout North America., and possibly elsewhere. Elder GR owners may (not) have the kind of funds available to support the initial and long-term costs of a GR, and their personal needs and preferences should be taken into account when considering the long-term development of the GR industry and incentive programs.

Measures of GR Satisfaction. Two additional questions measured original and current satisfaction regarding the GR with which survey respondents were associated. Among the 79% of participants who were familiar with the original GR, answers to this question reveal a slippage of satisfaction over time. Less than half of the 53 respondents (39.6%) indicated their opinion of the current GR was the same as the original installation. 19% of the respondents indicated their original GR rated 4 out of 5 on the Likert scale, where only 17% said the same of their current GR. A more significant slippage was noted among the 45% of respondents who rated their original GR at 5 out of 5, but only 22.6 % still held this opinion of their current GR.

Post-installation measure of GR failure.

Using criteria that delineates differences between levels of failure, surveyed ICI GR owners in Portland have provided evidence that indicates GRs there experience an overall *partial* failure rate of nearly 9%. The same criteria and representative sources indicate rates of post-installation *total* failures of 6.37%. Survey findings consistently point to specific issues related to but not always correlated with GR failure, including aesthetics, maintenance issues, plant decline, irrigation failures, cost over-runs, and marketing failures (in that order). Although separate from total failure-related issues, the snowballing of partial failure issues pushes the accounting of some failures into the total failure category.

Older GR technologies, which Survey #2 reveals have failed slightly more often, may still influence current perspectives of potential GR customers, in part because of negative media stories that are no longer valid. The perception (real or otherwise) of costs and other problems associated with GRs, highlight leak repairs and dramatic plant failure issues that are now easier to address, especially on newer structures, more so than GRs installed on older structures. Weed invasions receive less media attention, but also appear to be common issues among owners and managers, perhaps using other communication channels to share that once entrenched, weeds are difficult to fully resolve. The ripple effect of negative publicity, if not also reported litigation, plus enhanced standards associated with these types of failures could be a driver behind diminished installations. The lack of consumer maintenance guidelines and advocacy could additionally feed GR installation declines.

As, or more important, may be the period of time when GRs begin to fail and show need for refurbishment. In Portland, this period is now confirmed and demonstrated to be approximately six years. What is not clear is whether the doubling of the 20- to 30-year lifespan of structural membranes is dependent on a GR providing protective coverage that involves consistent maintenance, and other details.

Looking at the data graphically. Figure 18 highlights GR failure counts in a timeline format. The per year installation of GRs in Portland, Oregon is denoted by the line that peaks twice in 2010 and again in 2014. The clusters of failure occurring in the program similarly peak twice over two three-year periods starting in 2001 and 2006, respectively.

Smaller GRs were considered in the graphical analysis because their failure rates clearly stand out in tandem with the number of GR failures. The finding suggests that GRs under a certain square footage may not be worthy of rate-payer funded incentives, especially if their individual stormwater GrIS benefits are limited. Unless small GRs are clearly pursued as demonstrations with educational signage, they provide questionable ROIs.

Similar examination of Table 24, as well as Figure 18, with less emphasis on the bottom line and more emphasis on when the failures occurred over the years shows a definitive reduction in total GR failures. GR failures have occurred in clusters since the outset of Portland, Oregon's exemplary GR program, especially the three years at the turn of the 21st century, and again between 2006 and 2010 when more GRs were installed per year. Early failures were often tied to GR design and installation issues, but the association of the failure increases with incentive driven installation counts suggests a correlation worthy of further research. What is known already is that incentives are elemental to the current installation of GRs. What is unknown is whether incentives contribute statistically to the rate of GR failure, and if so, by how much.

Summary – PART II

Fortunately for GR owners, managers and representatives, they haven't experienced catastrophic failures, but they have experienced various levels of GR failure identified and

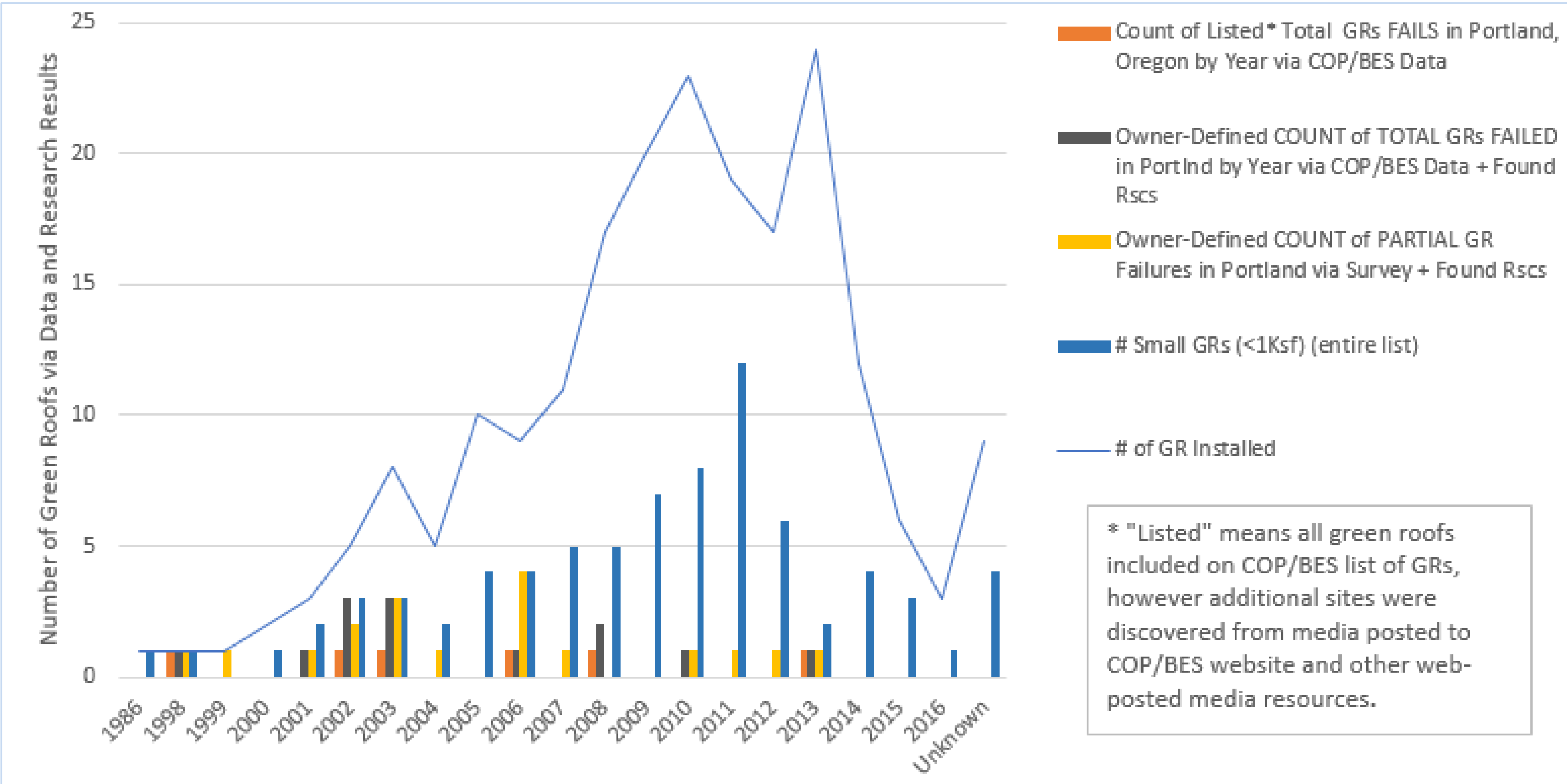


Figure 18. Summary of Portland, Oregon, green roof failures defined by COP/BES and by green roof owners (1986–2016).

defined by experts in the thesis. Among these, aesthetics rank highest the lowest rated concern of experts. To the degree that owners and their representatives do not experience many total failures, but do experience numerous accumulating partial failures, may drive the difference. The time-consuming minutiae of partial GR failures and external issues not considered by experts as associated with failure (real estate and insurance risks stand out) may be more important issues that influence whether or not a consumer pursues GRs into the future.

Summary – Surveys #1 and #2

The last analysis compares GR failure counts before and after implementation of Survey #2. Significantly different from experts is owner and representative perception of which problems are the most common and worthy of being prioritized. Table 24 distinguishes between GR sites that were surveyed and others in Portland that were not, and tallies the count GR failures discovered during the research process. Columns #2 and #6 are populated by data provided by COP/BES (2010). Additional failures beyond the "total" failures defined by COP/BES include those discovered in COP/BES online reports and via media reports. "Reinstallations," closed and abandoned GRs were similarly disaggregated from the available data.

Survey #2 Failed Green Roof Data by Year

Using the same categories of GR failure identified by experts (i.e., partial and total), mentions of failure issues were assessed for each GR in Portland, providing a count of partial and total failures in Table 25. In this manner, the experts' ranking of issues associated with GR failure are compared with Portland GR owners' listing of site specific issues experienced in their GRs. This calculation distinguishes between partial and total failures based upon the duration of failure, suggesting that application of failure categories to GR asset management may be useful.

Table 25.
Green Roof Failure Types and Counts Determined by Portland, Oregon, GR Owners, Managers, or Representatives

1	2	3	4	5	6	7	8	9	10	11
YEAR GR Installed (n = 204)	# Listed Total FAILS ([1]Srvy'd and Rmv'd)	# FAILS ([1,2]NOT Srvy'd and Rmv'd)	Total GR FAILS by Yr Surveyed	Surveyed Rate of Total FAIL/YR (as a % of Total)	# Listed Total FAILS ([1]Srvy'd and Reinstll'd)	# FAILS ([1,2]NOT Srvy'd and Reinstll'd)	# Listed Total FAILS ([1]Srvy'd and Abndn'd)	# FAILS ([1,2]NOT Srvy'd and Abndn'd)	All GRs FAILS by Yr	Non Surveyed Rate of Total FAIL/Yr (% of Total)
1986+/-			0	0%					0	0.00%
1998		1	1	10%				1	2	7.69%
1999			0	0%		1			1	3.85%
2000			0	0%					0	0.00%
2001			0	0%	1	1			2	7.69%
2002	1		1	10%	2	3			6	23.08%
2003		1	1	10%	1	1			3	11.54%
2004			0	0%			1		1	3.85%
2005		2	2	20%			1		3	11.54%
2006			0	0%	1		1		2	7.69%
2007		1	1	10%				1	2	7.69%
2008		1	1	10%		1			2	7.69%
2009			0	0%					0	0.00%
2010	1		1	10%				1	2	7.69%
2011		1	1	10%	1				2	7.69%
2012	1		1	10%					1	3.85%
2013			0	0%	1	1			2	7.69%
2014			0	0%		1			1	3.85%
2015			0	0%					0	0.00%
2016			0	0%					0	0.00%
Unknown			0	0%					0	0.00%
TOTALS	**3**	**7**	**10**	**Average**	**7**	**9**	**3**	**3**	**26**	**Average**
% of Total:	**1.5%**	**3.4%**	**4.9%**	**4.76%**	**3.4%**	**4.4%**	**1.5%**	**1.5%**	**12.7%**	**5.86%**
YEAR GR Installed (n = 204)	# Listed Total FAILS ([1]Srvy'd and Rmv'd)	# FAILS ([1,2]NOT Srvy'd and Rmv'd)	Total GR FAILS by Yr	Rate of Total FAIL/YR (as a % of Total)	# Listed Total FAILS ([1]Srvy'd and Reinstll'd)	# FAILS ([1,2]NOT Srvy'd and Reinstll'd)	# Listed Total FAILS ([1]Srvy'd and Abndn'd)	# FAILS ([1,2]NOT Srvy'd and Abndn'd)	All GRs FAILS by Yr	Rate of Total FAIL/Yr (% of Total)
1	2	3	4	5	6	7	8	9	10	11

(1) Rates of failure discovered via survey/literature search are greater than those reported by COP/BES.

This indicates that if all sites were surveyed, the rate of total and failures would be higher.

(2) Although not surveyed, owner/manager communications and/or media mentions confirm failure issues and counts.

(3) Square footage of closed sites, incomplete installations, or real estate assets sold, not included in tally.

(4) Total failures distinguished from Partial failures by COP/BES definition: Total = GR Removal or Reinstallation (not including real estate on the market).

Chapter Summary

Issues related to leaks, plant losses irrigation and maintenance, and the broad range of expert cited "intentions" tend to obscure an owner's GR priorities and criteria of GR. The results of both surveys implemented highlight differences between Portland's (originally implicit, but now measured) 2.94% rate of reported *total* GR failure and the rates of failure separately identified by Portland GR owners and managers. The difference between these values provides a baseline gap that is small, and a point of comparison with which Portland, other municipalities, can begin to analyze and enhance GR incentive programs for the sake of GrIS resilience.

Important summary values in Table 26. include the average number of years before GR/roof issues occurred (5.96 years). Despite the minimum 20-year assumed longevity and roofing membrane protection promised by the industry and agencies, issues and partial failures appear to be occurring at this period of time that synergize into total failures in a full 25% of the Portland sites surveyed (equivalent to nearly 7% of all sites in the Portland ICI GR population.

Table 26.
Summary Comparison of Expert to Owner/Manager Definitions of Green Roof Failure

# Sites Surveyed (n=52) **% of Total Count: 25.49**	**Total # of ICI GRs Installed**	Average # of Years Before GR/Roof Issues Occurred	Agency-Defined # of Listed Total FAILS ([1]Removed) = Total Fail	Agency-Defined # of Listed Total FAILS ([1,2]Reinstalled) = Total Failure	Agency-Defined # of Sites ([1,2]Abandoned) = Partial Failure	Agency-Defined # of Sites ([1]Refurbished) = Partial Failure	Agency-Defined # of Listed Sites Closed[1,3] = Partial Failure	Industry-Owner-Defined Total FAILS by # of Green Roofs/Year[1]	Industry-Owner- Defined Partial FAILs by # of Green Roofs/Year[1]	Industry-Owner- Defined Average TOTAL Failures/Year
TOTALS	**204**	**5.96**	**6**	**7**	**6**	**9**	**4**	**13**	**18**	**20.17**
Averages Relative to Total Count of GRs			**2.94**	**3.43**	**2.94**	**4.41**	**1.96**	**6.37**	**8.82**	**Avg.**

Chapter 5 – Discussion and Conclusions

Defining and measuring green roof (GR) failure is a thesis objective that has been met via implementation of expert and owner perspective surveys. While GRs fulfill a small market niche among other green infrastructure (GrIS) options that benefit urban resilience, the measure of GR failure is considered an over-arching reason to pursue the thesis topic because GRs become municipal utility assets when they have been incentivized. Building upon an overview of potential GR components, interest groups, development drivers and constraints, potential outcomes and associated failures, we learn that ecoroofs (ERs) that benefit urban infrastructure are in many ways different from GRs used primarily for private owner benefits and amenities.

Although GR failure definitions have been framed, the thesis does not measure the trade-offs of stormwater abatement (as well as energy savings) lost (or gained) by utilities seeking to expand infrastructure, when a GR, rather than an ER, is installed. Separate from ERS, externally developed GRs are, to various degrees, managed by owners willing to pay costs associated with benefits beyond the ecosystem service needs of municipal utilities. Owner-sought benefits are sometimes industry-driven, and have the potential to conflict with, or minimize, the needed return of stormwater management (but possibly support the pursuit of utility energy savings). Such conflicts might be appropriately considered a program failure from the stormwater utility perspective. As a result of this association, one question that stands out among all others presented throughout the thesis is, "What is the most appropriate operational definition of green roof (GR) failure?" Given the multiple criteria regarding GR failures that are evident, effective failure analysis using the isolated definitions derived remains incomplete.

Comparing Hypothetical Values with Reality

Review of hypothetical priorities of GR interest groups, and input from GR experts that associates varied issues with GR failure further reveals criteria differences between the priorities of utility agencies, GR industry members and educators, and GR customer interest groups.

Table 27, revisits the GR failure categories originally established in Chapter 2. Upper-case bold "**X**"s indicate a higher priority than the not-bold lower-case "x"s. This table reiterates the limited interest that municipal utilities have in priorities held by other interest groups.

Table 27.
Stated Priorities of Green Roof Interest Representatives

Severity and/or Duration of GR Failure	Issues Associated with Failure Type	Utility Agency Priority	Industry Priority	Customer Priority
Partial GR failures transitory issues that are repairable without GR removal	1. Client-stated dissatisfaction, whether related to aesthetics, maintenance, costs or other issues.		x	**X**
	2. GR safety issues associated with access not addressed in original GR design.		x	**X**
	3. Warranted and other repairs, and/or temporary GR removal, regardless of cause.		**X**	**X**
	4. One-time plant failures involving <25% of installed, occurring within 1–3 years.		**X**	**X**
	5. Cost overruns not collectively exceeding the customer's stated cost definition for a major failure associated with GR, but not necessarily the structural membrane.		x	**X**
Total GR failures entrenched issues that tend towards GR removal or involve major GR or roofing membrane repairs	1. GR-related cost overruns that collectively exceed the customer's stated cost for major failure of the GR.		x	**X**
	2. Structural leaks, regardless of cause in association with GR and/or relative to the roofing membrane beneath it.		**X**	**X**
	3. GR drainage issues resolved with GR removal.		**X**	**X**
	4. Multiple failures of installed plants >25% occurring within 1–3 years.		x	**X**
	5. Repeated partial failures.			**X**
	6. Any partial failures listed that escalate into temporary or permanent GR removal.			**X**
	7. Owner pursuit of litigation to recover costs related to failures listed above.		x	**X**
Catastrophic GR failures limited to complete structural failures	1. Failures related to ineffective GR engineering.	x	**X**	**X**
	2. Permanent structural damages associated with membrane failures (leaks).	x	**X**	**XX**
	3. Permanent GR removal.	**X**	**X**	**X**

Representative Priorities of Green Roof Interests

While Table 2 in Chapter 2 lists the breadth of potential public and private GR benefits possible among GR interests, the categorization of priorities among these interests by failure severity verifies the originally hypothesized priorities. The failure criteria established by each interest in light of their priorities, as shown in Table 28, below, is discussed in the following summaries which highlight the differences of GR objectives held by individuals who participated in Surveys #1 and #2. These perspectives translate into failure criteria that influence the long-term rate of GR installations. Unmet objectives, which should be measured by utilities, can become media-amplified failures that become reasons to not participate in the GR market, overall, or to remove GR assets upon which utilities are increasingly dependent. If failure data were consistently analyzed in conjunction with the reasons for GR failure that necessitates removal or reinstallation, the information would reveal patterns of benefit to all interest groups identified.

Municipal Utility Perspective

Lacking an established operational failure definition, the utility agency perspective was defined using implied data counts supported by expert responses obtained from Survey #1. The municipal utility perspective of GR failure includes catastrophic failure (building collapse) and GR reinstallation (regardless of cause), but only removed GRs qualify as having failed. In addition to disaggregated results of Survey #1, currently available data from a variety of public sector organizations imply that failure and success of GRs is otherwise currently measured first by the number or square feet of installations recorded that, secondly, remain in place (Chicago GR Data, 2012; List of Existing GRs, Melbourne, Australia, 2012; Portland Ecoroof Data, 2010; List of GRs, Seattle Public Utilites, 2015).

Table 28.

Comparison of Green Roof Interest Priorities, Failure Criteria, and Measures of Green Roof Failure

Interest Groups → **Categories of Concern ↓**	**Agency Representatives**	**Industry Representatives**	**GR Owners** (subjective)
Green Roof Goals and Priorities	*(listed in order of priority)* • Stormwater retention and water quality • Energy conservation and UHI reduction • Carbon sequestration • Creation of habitat	*(listed in order of priority)* • Fulfill owner/designer intention(s) • All items from *Agency Representative* priorities +	*(varied owner priorities)* • Private benefits • Avoided costs and owner commitment • *Industry Representative priorities*
Failure Criteria applied to Institutional, Commercial, and Industrial GRs in Portland, Oregon	• Structural failure • Any GR removed *Criteria implicit among GRs listed by City of Portland BES; (list predates thesis)*	• Structural failure (engineering) • Unsafe or limited GR access • Plant losses • Membrane repair within warranty • Repair of improper or incomplete contractor GR installations • Contractor affects GR media • Pre-installation drainage issues • GR membrane lifespan shorter than conventional roofs *Criteria obtained from 41 global expert surveys defining operational GR failure*	• Structural failure (maintenance) • Owner-created leaks • GR removed to sell the building • No warranty for products and services • Multiple plantings required • Post-installation regrets • GR abandoned *Criteria obtained from 51 owner/manager surveys*
Outcome of Criteria Measured	**COP/BES green roof list: failures = 2.94%;** (reinstalls are excluded)	**Average rate of partial failures in Portland's ICI GRs: 6.37%**	**Likert scale of future GR purchase + Portland's average total fail: 8.82%**

Portland, Oregon's institutional, commercial and industrial (ICI) ERs and GRs specifically illustrate a definition of GR failure that is limited to the agency's interest in stormwater management. Toward enhanced adoption of GRs, these criteria have been broadened to include less tangible environmental interests seeking to gain ground with habitat restoration, and may eventually include needed carbon sequestration. However, the latter benefits are hard sells given the non-monetized ecosystem service values that they offer. In addition, the habitat benefit is somewhat limited to sites providing plant-diverse (rather than monoculture) habitats.

Green Roof Expert Perspective

An alternate definition of GR failure was constructed by a wide range of international GR experts using disaggregated data from Survey #1. The expert perspective of GR failures predominantly refers to the "intention(s)" of the GR designer or owner, and includes structural failure resulting from an improperly engineered GR, as well as GR removal. The concept of intention is a catch-all that accommodates countless failure issues that are then harder to assess without assigning consistently weighted monetary values and risk potentials. Expert definitions of GR failure in Survey #1 are not considerably different from owner criteria, but the issues are better defined by owners in Survey #2.

In Survey #1, expert survey respondents equally cited (at 42.5%) "intention" and issues related to GR vegetation as primary features that associate with GR failure. Of the 17 respondents citing inability of the GR to meet intention as the primary failure definition, six emphatically stated that all other aspects of GR failure would fall under this definition. The 42.5% value does not include responses citing concerns with unintended plant-specific biodiversity and weed invasion (totaling 12.5%); respondents citing inability of the planting selection to thrive in the given climate (totaling 5%); or the value associated with plant-based aesthetics (totaling 15%). Plantings issues are clearly one of the highest priority criteria. While visibility of plant health and aesthetics of a GR is a simply defined issue, what evolves is work for owners and managers influenced by a significant number of dynamic horticultural factors.

Leaks related to the GR (distinct from the roof membrane) were the next most cited expert issue at 25.0%. Discussion of leaks generated sensitized responses from both participants in the survey and individuals outside of survey communications. Last of all, stormwater-related issues garnered 20% of Survey #1's failure associations. This distinction marks one of the more important differences between agency and expert failure definitions. The lack of consistency may diminish both interest's ability to achieve their objective goals. Expert interests lastly include a built-in interest in marketing of GR products and services.

Educator Perspective

Educators' GR failure criteria were established from the same survey #1 targeting experts worldwide. Responses highlighting leaks, planting media, drainage issues and roofing lifespans provided by this group stand out somewhat, especially in Table 10 where all interests perspectives are ranked side-by-side. The priorities relate to functional aspects of a GR, and may reflect focus upon issues that are cornerstones of many academic programs. To the degree that the opinions of educators are different from those of other interest categories may warrant increased collaboration both within the industry and across industry boundaries to consider the research and/or industry training being pursued, and whether or not academic research results are being assimilated by the larger GR industry.

Owner Perspective

An owner-driven definition of failure was constructed using data from Survey #2. Owners are composed of a wide variety of interests including managers of public and private commercial, industrial and institutional facilities, with varied levels of funding available to them. Most of these people are motivated by utility and maintenance cost avoidance, and install GRs for private benefit amenities over public benefit amenities; others are motivated by promotional benefits via symbolic certification. Additional others are motivated by sometimes contradictory interests in aesthetics, ease of maintenance, ROI in the form of property resale value, roofing membrane longevity, plus concern for financial risk minimization and safety.

Poor plant performance and issues that require consistent, knowledgeable, timely, and sometimes expensive maintenance inputs are rated as higher priority failure issues than leaks, the most commonly cited expert issue. Distinguishing between public and private benefits is also important to GR owners. Public benefits are clearly externalities paid for not just by the pool of utility customers, but more so by GR owners choosing to participate as maintainers of privately held stormwater infrastructure assets.

Publicly owned and managed GR interests maintain these perspectives where funding is tight and where staffing is limited in capacity to fulfil the standard maintenance that comes with GR ownership. A more optimistic perspective of the inputs that consistently provide successful GR results is evident where funding is managed indirectly, and/or is readily available. Nevertheless, government requirements to accept the lowest bid makes some institutional GR failures worse from the start. Some of these GRs were also found to be installed without the benefit of trained staff who would be tasked with their maintenance. Others were found to be installed without the longer-term funding that proper management of GRs requires.

Another important distinction between the financially conservative GR owner perspective and the industry perspective is unrealistic owner interest in low- to no-maintenance GRs without sacrificing promoted aesthetics. Minimal maintenance is sometimes promoted by industry representatives, but not always in league with the trade-offs to be expected. Both owners and industry representatives tend to believe that costly automated irrigation might resolve the issue. However, survey respondents note that irrigation was not helpful if weeding was not also addressed.

Because GR owners and managers often lack time and horticultural knowledge, they may always need support to help them establish their GRs, if not maintain them long-term. This is less of an issue for non-accessible sites, but critical to the indirect promotion of GRs among owners of GRs that are visually or otherwise accessible to occupants. Owners will otherwise benefit from thoroughly educating themselves, along with building occupants, toward the understanding and appreciation of the numerous and complex dynamics involved with GR installation and their maintenance – before committing finances to the pursuit of potential GR benefits. Unless ongoing maintenance is a warranted or contracted element of a GR project, industry providers are otherwise said by owners to overlook owner interest in avoiding maintenance that involves time, horticultural knowledge, and physical labor.

Portland's incentive program exemplifies experimentation with owner-managed GRs that may or may not support the future of GRs as a GrIS solution. The take-aways could be "do it right, or don't do it at all." Especially when experimenting, GR product providers and utility incentive programs could be more transparent about potential risks. Owners, especially of public institutions, need to be aware of and willing to experience potentially costly mistakes. Research cannot and should not occur risk-free, but expectations of maintenance staff who may end up maintaining GRs, among other users, also deserve clear communication ahead of GR installation, and, perhaps, the chance to limit their installations.

Green Roof Industry Perspective

As a subset of GR experts, members of the GR industry are important to the equation because of their influence on the overall GR industry. Owner desire to avoid costs understandably differs from the industry's interest in selling products, warranties, and services, usually at the highest possible value. It may not be practical or appropriate for industry (and/or agency incentive) providers to assess an owner's commitment to necessary GR maintenance, including irrigation (at least for the duration of GR establishment). The benefit, however, of more diligence in this category may create better GR installation rates and increasing marketability of this GrIS niche. Where industry and municipal utility interests can reinforce owner understanding with price incentives and/or educational support, they may also see fewer GR failures.

Membrane Lifespan vs. GR Failures

Membrane lifespan is important to the consideration of priorities but doesn't fit into any one interest category. Although improving over time and with new technologies, membrane lifespan is among the more contested issues still debated by GR experts cited in industry literature. Among owners and managers, membrane leaks are also a primary issue associated with GR failure. Measuring longevity of roofing membranes and GR installation remains incomplete, but is elemental to data gathering and the asset management process.

The debate that remains unresolved points to membrane failures occurring before the installation of a GR an issue highlighted in recent media-about GR/roofing failures at three public facilities in the Pacific Northwest (Budnick, 2015). These litigated installations exemplify failures that encourage reconsideration of whether or not GRs are truly separate from the roofing components on which they are built. In many cases, complete removal of the GR or sections of the GR was elemental to the resolution of the leakage. As defined previously, permanent GR removal qualifies as a total failure. When GR removal from structures is required to repair membranes, how often are they fully replaced? How might a utility otherwise track the changes that occur among the GRs in their collective GrIS system? Both of these questions would benefit from further research.

Such incidents further highlight the gravity of the low bid requirement that can allow poorly qualified contractors to successfully underbid a project. Ineffective installations and/or protection of pre-installed and defective membranes may be difficult to prove without the expense of litigation (a currently externalized cost). The addition of litigated GRs to permanent media records also negatively influences future GR consumers. The media perspective of failure is nearly as important a market driver as any of the others discussed throughout the thesis.

Another market-based consideration is the promotion of membrane longevity as a benefit of GR installation. The lifespan benefit may be a primary marketing factor that secures a GR sale. Portland's yearly failure data, which includes the number of years before GR issues occur, provides an average of 5.96-years. This is the point at which GR refurbishment appears to be an industry norm. That the five- to six-year mark is when refurbishment of GRs is expected by members of the GR trade undermines the marketed benefit suggesting GRs extend or double the life of a roof's membrane. The caveat is that membrane longevity is dependent on whether or not a GR is *reliably* maintained, where owner WTP plays a critical role.

Measurement of a utilities' vegetative roofing assets should, at minimum, be considered to test the conundrum of membrane lifespan. In Portland, the current average age of all ICI GRs is only 6.7-years. Industry focus on membrane lifespan may otherwise be a canard that cannot be proven with post-installation GRs until more North American installations reach the 20 -30-year age range.

Outside of costs to maintain and refurbish ERs carried out by municipalities, like Portland which manages its own GR installations, are the maintenance and refurbishment costs of externally owned GRs managed by owners or their contracted representatives. Annual per-square-foot refurbishment values among GR professionals currently range between 5–10% of the value of a new GR, which is dependent upon the accessibility of the GR. As evidenced in

Survey #2, and relative to owner WTP, this value is, generally, not a hardship. However, unless an owner or GR investor is forward-thinking about the GR they are maintaining or about to purchase, this value may be forgotten or avoided… until its need is unavoidable.

Estimated values obtained for the refurbishment consideration are inexact, however, because they cannot accommodate for price variances associated with GR accessibility, thus adding weight to the importance of the consideration. How many GRs already, or eventually, need to be located at the top of multi-story buildings (another value to track in the agency's GR database)? How many types of proprietary GR refurbishment approaches are available in local marketplaces? Research regarding the variety of variables beyond GR type still needs to be pursued and factored to obtain a balanced risk and ROI perspective and reasoned LCCAs.

The five- to six-year refurbishment statistic appears to be a partial failure reality that supports pursuit of asset management from the onset of GR project planning. The thesis author hopes for continuing communications among GR industry interests and proponents to address the debate. This may possibly be driven by further litigation over failed roofing lifespans where GRs have been installed toward that end.

Generational Market Influences. The thesis author also suspects the potential for failures among overconfident customers could increase, or a lackluster rate of GR installation may continue as owners choose roofing options that don't require the expenses for manual labor that vegetative roofing involves. The impending retirement of baby boomers may cause a diminishing interest in high altitude garden maintenance and potentially risky commitments for real estate assets where minimal insurance and liability expenses have become a priority.

Early adopters and real estate-savvy recipients of incentives, on the other hand, could lead the GR market out of the doldrums. Both of these optimistic interests have "profited" on their GR installation because they either did the work themselves and used non-traditional supplies, and/or the incentives provided lucrative real estate advantages. Market-savvy developers and other early adopters can be expected to continue to seek out ROI but their involvement supports the trial and error of newly developed sustainable infrastructure.

Portland's demographic is environmentally conscious and, as of 2010, approximately 19% of Portlanders were under the age of 18 (Gowdy, 2010). In 2017, men and women of Portland older than age 60 comprised slightly more than 15% of the population (SuburbanStats.org, 2017). But neither youth or advanced age confer the kind of horticultural knowledge required to successfully manage a GR or an ER, especially those with mixed species and media depths. Both technologies come with a variety of needs that cannot be put on hold without failure consequences. A broader marketing analysis would more effectively answer these considerations, especially in locations whose demographics are different than that of Portland, Oregon. A similar LCCA analysis comparing ERs and GRs would also be beneficial.

Whose Definition of GR Failure is Most Important?

A still unanswered issue that improved failure data would clarify is whether one approach to installing GRs ought to become the norm. Clearly, owners and managers of GRs define failure somewhat differently from GR industry interests, and very differently from the agencies and educators who directly and indirectly promote GR installations. This results in conflicting inter-industry interests such as energy savings vs. stormwater management among utility agencies, as well as conflicts between the gamut of intentioned benefits and amenities sold by planners, and/or sought by GR owners. Recognition of this variance doesn't discount objectives that each of these interests pursue. GR owners have reasonable private benefit needs and interests that need to be better addressed, but the opposite could also be stated. In addition to the lack of horticultural skills applied by owners, lack of alignment on needed GRs outcomes highlights why GRs can but don't always provide the benefits they are promoted to offer.

Part of the issue lies as much in the need for stormwater management as it does with the need for other benefits that can run counter to it. An example is the appropriateness of irrigation of GRs in a water-limited eco-biome, along with applications of leachable fertilizers. These practices can artificially aid the maintenance of highly aesthetic GR installations, UHI remediation that benefits the community and energy utilities, and provide energy savings to GRs with solar PV systems. The outcomes of water pollutants and minimized stormwater management objectives, however, are contradictions that have as much or more economic value as the energy savings. Portland, Oregon's need for additional ERs for stormwater infrastructure and water quality protection may or may not provide an exemplary answer. Perhaps it is possible that both can be separately accomplished on separate installations or on installations with specified management practices.

Post-installation performance evaluations and LCCAs need to measure both pursuits in terms of data, but also in terms of marketing. If the slightly less aesthetic approach of ERs were mandated or otherwise enforced, for example, would the industry and/or potential customers rebuke it by installing fewer GRs, overall? The same question could be asked of GRs on visually accessible buildings with reflective and not always aesthetic arrangements of solar panels. Are the benefits of either technology compelling enough to regulate their inclusion?

Summary of Failure Perspectives

Two points of agreement regarding the operational definition of GR failure among GR owners, industry experts, and agencies providing GR incentives are evident from the findings of this thesis. Those points relate to catastrophic (i.e., structural) failures and the permanent removal GRs from project sites. There is otherwise more in common regarding GR failure definitions between GR owners and industry representatives than there is between either of these interests and the agencies that incentivize GRs.

Development and long-term input of GR data like that maintained by Portland, Oregon's Bureau of Environmental Services (COP/BES) and furthered via this thesis makes sense because it provides the baseline that failure analysis and fully weighted asset management requires. The Portland case study exemplifies that their implicit baseline may currently be under-reported or incomplete. However, the values indicate that the agency's count is within ten points of the GR failure referenced by owners and managers. That gap can be overcome by bringing variances of the perspectives into better alignment. The effort would require group participation and communication but aid the long-term growth of the GR industry and the use of GRs to ameliorate climate change issues.

Addressing Issues Enabling Green Roof Failure

A short list of the more obvious partial, total, and other GR failures that the thesis reveals are plant losses due to lack of timely maintenance and irrigation, GR aesthetics and GR leaks. Less tangible issues related to GR failure undermine sought after amenities and designed intentions, including real estate transactions and financial opportunities. These are, in many ways, secondary issues that occur as a result of other causes, such as limited horticultural knowledge and choices to which GR consumers over-commit that result in poorly managed GRs.

Horticultural Skills for GRs

Among the people surveyed for this thesis, individuals with effective access to, or an existing understanding of horticulture in terms of plant, water, and soil dynamics were found to be the least plagued with GR failure or other problems. However, after accessing hundreds of consumer and academic articles and webinars, the author is wary of suggesting that a chapter in a book, or two, or even an entire book addressing these topics could possibly address all of the

GR issues and questions a time-starved non-gardener might ask about GR horticulture (if they knew what questions to ask). Counterintuitive beliefs and tenets that rely on use of chemicals for short-term benefits need to be addressed because they add to a broader form of GR failure.

A basic understanding of horticulture is an essential foundation to the most effective function of all GRs that, like failure, does not appear to be fully addressed in consumer literature. Therefore, unless a GR consumer buys a maintenance contract from a reputable provider, the responsibility for a wide range of necessary GR inputs, such as maintenance and irrigation, belong entirely to the GR owner who is typically unprepared for the horticulturally demanding task of long-term GR maintenance. Additional research might verify the need for broader horticulturally-oriented consumer advocacy in order to strengthen not just the appropriate installation of GRs, but also their long-term management to the benefit and appreciation of all parties involved.

Utility agencies and the GR industry already acknowledge this issue by offering public and professional education opportunities and training toward certification. Portland has offered public trainings in league with the Green Roofs for Healthy Cities and the Green Roof Information Thinktank. Agencies similarly encourage consumers to hire not just certified, but experienced GR professionals. Agencies can also implement minimum certification standards and associate minimum specifications with incentives offered for GR installation.

Irrigation vs Stormwater Abatement

There is a consistency among GR failure issues that coincides with use of irrigation that deserves to be understood and measured as an extension of this thesis. One aspect of this consistency lies in the perception among many owner/manager survey respondents that GRs must have water to thrive to be aesthetic. The need for short-term irrigation is not a well-understood given for GRs, especially those installed at the beginning of a growing season.

Irrigation is also critical to the establishment of GR plantings over the first one-to-three years following GR installation, but often down-played as an effort or expense. The irrigation period beyond plant establishment also remains debated, and will vary from one eco-biome to another. A second aspect regarding the consistency of GR failures where irrigation is applied is related to failures associated with poor irrigation system design, system breakdowns or misuse that contribute to leaks, media erosion, wasted and polluted water, and especially to plant failure from over-or under-watering. Additional research on these aspects would be beneficial.

However, beyond the establishment of a vegetated rooftop, irrigation (and, to a lesser degree, maintenance) are nearly antithetical to the stormwater objectives needed by utility agencies for the expansion of infrastructure beyond pipes and pumps. This is especially true in municipalities where rain gardens and other GrIS approaches are not an available option because the real estate at and below-ground-level is already occupied by development. Unirrigated GRs are better at accommodating increasingly severe precipitation events associated with climate change. Irrigation of GRs undermines the needed water-holding potential that offsets CSOs.

Alternately, irrigation and maintenance inputs may be considered necessary by GR owners and managers for maintenance of certain GR designs. These designs include GRs that intend to provide aesthetics via exotic or lush plantings, which require regular irrigation and maintenance to keep the plants consistently attractive. While allowance of this approach by incentivizing utilities may be needed to maintain access to the industry's marketing of GRs, it undermines the stated objective of stormwater management, and can confuse consumers.

GRs might also employ irrigation to minimize UHI, to create energy-saving thermal insulation, or support low irrigated vegetation that enhance the function of PV solar panels. The benefits sought by agencies for stormwater management may, or may not be as beneficial to a

GrIS that provides energy savings. Cost benefit analyses comparing these pursuits is a tangent of the thesis that deserves more research. These opposing (and sometimes assumed) needs for on-going irrigation and maintenance otherwise explain why the utility-driven pursuit of GRs is divided into either/or benefit categories.

Further, water quality concerns related to GR maintenance practices on irrigated (and unirrigated) GRs exist when chemicals are used to enhance, minimize or eliminate the growth of specific plants and pests because the chemicals get washed into downstream water bodies. Non-point source pollution is nearly impossible to regulate but continues to damage water systems upon which humans rely for a wide range of beneficial ecosystem services that remain only partially understood. Although it is considered mandatory in landscapes, normative use of chemicals on GRs is often driven by well-meaning individuals whose job security depends upon keeping their customer's GRs looking green. Research is limited that not only proves otherwise, but which offers cost-effective alternatives that are less damaging to the environment.

In August of 2016, the thesis author toured mature ERs in Portland which demonstrated that if ERs were well enough established with appropriate media mixes and weaned from management but provided maintenance at least 1–2 times per year, they needn't become overrun with weeds and could survive without irrigation in Portland, Oregon's current eco-biome. The selection of particular plants and the use of volcanic cinder media and mulches make these ERs look different (not necessarily worse) than the lush landscape images found in coffee-table books and PR used by most businesses and utility agencies. Achievement of an irrigation- and maintenance-free GR may be possible, but may be difficult to market beyond the currently limited rate of GRs already installed.

Although medium- to low-tech, often unirrigated, "extensive" veneer-type ERs receiving one to two maintenance events per year are well-demonstrated by Portland, research verifying the possibility of the same outcomes in other eco-regions would need to be pursued. Adoption of Portland's ER approach also suggests that GR owners would need to become comfortable with some forms of seasonal plant dormancy and invasion of certain "weeds," such as low spreading grasses that benefit unirrigated and low-maintenance GRs (Carey (Greenroofs.com Virtual Summit), 2011). Where a GR is less or not visible or accessible to building occupants, veneer or modular installations could be pre-composed of plant combinations including "weedy" species that tend to result over many years, especially where refurbishment is a low priority.

Effective Marketing of GRs

Values emerging from the failure analysis of GRs in Portland, Oregon have implications on how GRs are marketed. Despite the availability of incentives to support installation of GRs as a form of stormwater infrastructure expansion, market penetration of GR technology has yet to surpass 5% of the rooftop acreage in Portland, Oregon, and less than 2% in Chicago, the periodic leader in the count of GR installations. Industry consideration that includes examination of how choice architecture is applied as a marketing tool is encouraged to enhance market-based outcomes. Additional provision of habitat to maintain species at risk and carbon sequestration may be among the aspects that attract participants. Need for livable green space for humans is also becoming a valued benefit that may prove attractive as a market driver. Although this topic is only slightly tangential to the narrow thesis research regarding the definition and rate of GR failure, it may help explain the way that GR marketing by utility agencies and the industry can undermine GR installations. Application of issues learned to the even larger niche of GrIS is similarly important.

Owners and managers of GRs who cite aesthetic failures also state or suggest that they feel they have been oversold on products and single season aesthetics that don't meet their expectations. The strongly visual marketing devices to which these GR consumers originally responded were also noted for including statements that led them to believe that all GRs perform equally in terms of aesthetics and/or ease of maintenance when the matter is dependent on a significant variety of horticulturally technical factors (personal communications, A. Chomowicz, March 13, 2017). In this way, partial failure issues cited by owners and managers of GRS are associated with the contradiction of agency and industry aesthetics and sustainability objectives used to promote GRs. These failures don't involve the function of GRs, but do involve consumer confusion related to the choices and associated trade-offs consumers must make.

Both agency and industry interests promote the installation of GRs or otherwise market them through attractive visual imagery that highlights GRs when the installations look their best; COP/BES promotions are no exception. Without sustained maintenance, it can be difficult to convey to owners that such floriferous results are not the norm, especially year-round, but that other good and not so good seasonal aesthetics can be achieved, or respectively, avoided.

The Ecoroof Image – Aesthetics in the Eyes of Beholders. As noted earlier, inclusion of sites with naturally occurring moss and "weed" growth among GRs on the COP/BES list of sites signifies this kind of ER provides stormwater benefits. Research verifying whether or not a naturally mossy or weedy ER doesn't damage building membranes may reinforce the pursuit of these outcomes. Another approach that might benefit this process is promotion of specific seed and media specifications that enable the achievement of a "climax" natural GR, along with guidance toward initial maintenance needed to create such growth.

Portland's GR tours and demonstration ERs are otherwise appreciated by potential and existing consumers, and illustrate the aesthetic potential of mostly unirrigated GRs that similarly provide aesthetics with minimal weed management. However, the ER approach is reasonably different from the GR design and management that is promoted by industry representatives who provide planning, installation, and maintenance. Were consumers to successfully adopt the approach only subtly preferred by Portland would help minimize two of the most commonly cited inputs assumed to be necessary for GR success (irrigation and maintenance) that frustrate GR owners, while helping Portland extend its stormwater infrastructure system. As with general landscaping, experiential understanding of horticulture aids failure avoidance associated with planning, plus initial, and ongoing, seasonally varied GR needs.

Regardless of whether or not an owner provides maintenance, ERs provide stormwater management while protecting or minimizing use of local water resources. Without the need for expensive irrigation systems and associated system maintenance, plus *eventually* minimized growth of weeds to manage, ERs are understandably attractive to owners who have limited finances, few horticultural skills and limited time and ability to access their roofs for maintenance and watering (personal communication, R. Meyers, August 9, 2016). As the current generation of Baby Boomers ages, and thus has an increasingly limited ability to maintain rooftop installations, the value of natural GRs, as defined by these consumers, may become more obvious. However, ERs (natural or otherwise) may not be the kind of GR customers would currently desire without substantial re-educational and normative-changing persuasion. Nor does these types of installations excite members of the GR industry who would rather sell the latest innovative products and services.

Dated Marketing Resources

The Greenroofs.com web portal (Velazquez, Velazquez, & Family, n.d.) represents an appreciable marketing database with project images, site data and initial post-installation images of a variety of GR projects being researched for this thesis. This promotional website tracks the total count of projects and square footage of all green roofs ever installed. In addition to paid advertising in the margins of the site, project information is available for nearly

1,700 GR installations located around the globe. The website notes that postings are "from published public accounts and individual project stakeholders..." and are "…offered 'as is' for informational purposes only…" The site text further states that the accounting (assumed to reference both project sites and their related details) "…is not complete…." In addition, the database is considered "…an ongoing open-source, community-based transparent, living research document. Errors in a database of this magnitude are very likely…" (Velazquez, Velazquez, & Family, n.d.).

Greenroofs.com project information shows dates of GR installations, but is otherwise not date-stamped, nor does a moderate percentage of the information appear to tell complete stories about each of the projects posted. Project details *are* important to consumers who endeavor to assess the ROI of potential GR investments while also considering the trade-offs of the significant variety of GR components and related services on the market. Despite the disclaimers posted, the information is considered misleading because it presents *only* positive aspects about posted projects. Failures are glossed over or superficially evident among projects lacking images and/or affiliation with project partners, who otherwise benefit from the promotions associated with each posting. Without points of reference, consumers and others who are not familiar with the fact that a number of GR installations posted at Greenroofs.com have experienced, at minimum, partial failure issues, if not total failures, may come away from the site thinking that the installation of GRs provides consistently positive results.

It is possible that keeping failed projects listed on the site adds to the total count and square footage of green roofs installed around the world. The pursuit of this kind of value appears to fuel both the industry and agencies that compete against one another for the most GRs installed. Although the numbers look enticing, they are ultimately misleading, if not inaccurate, because they do not convey the count or square footage of GR projects that have been removed (regardless of the reasons for their removal). Nor are these GR figures compared to other, sometimes competing, green infrastructure options.

The more recent competing data warehouse for GR projects is the Landscape Architecture Foundation's (LAF) Landscape Performance Series (Landscape Architecture Foundation, 2016). This progressive database provides case study details of selected sustainably oriented projects, including a listing of beneficial outcomes associated with each project. This visually informative site offers the same kind of dates installed and square footage of installation information as Greenroofs.com. In addition, selected projects include metrics and methods that begin to quantify environmental, social, and economic benefits that are, generally, more specific to this thesis research. What remains undocumented, however, are the "lessons learned" from failures discussed. It is this kind of transparency that makes improvements within the industry possible while informing consumers about the maintenance responsibilities in terms of time and money required to own and operate GR projects. It is hoped that the site will candidly highlight issues experienced with each of the projects posted. This is also the kind of information that reinforces objectives of the landscape architecture trade which states its interest in minimizing the global impact of development as well as meeting the rigorous demands of adaptation to climate changes that are occurring with increasing frequency and magnitude.

The triple-bottom-line question that begs an answer is, "How often can any of us search the web for product information and find both glowing and/or negative reporting about the same product?" Psychology research reveals that when available information is contradictory or, worse, too information-rich, consumers start to "check out" in pursuit of something simpler.

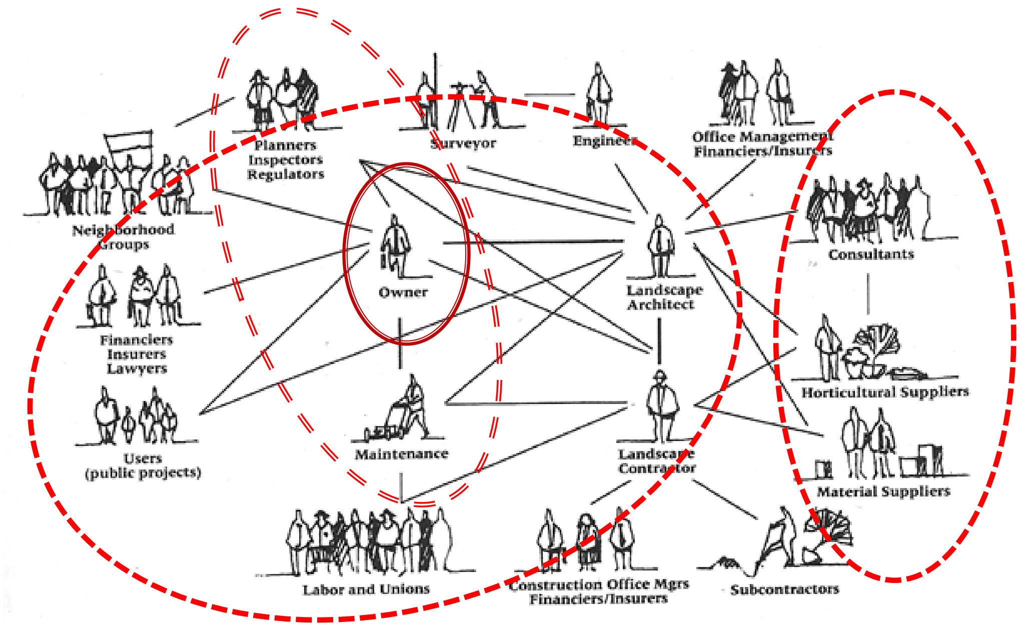
When the thesis author endeavored to learn more about GR installations, these and other "portfolio" promotions posted independently by project partners about GRs were readily discovered. Information regarding the GRs at The Evergreen State College (TESC) were among those sought to compliment the thesis. Among the first installations at a state-owned facility, the GRs at TESC were originally examples to be followed. Accolades were bestowed upon the team of professionals involved with the campus structures in 2005. The problem was that the information (again, rarely date-stamped) was patently false. Although wrong, the information is as optimistic and enticing on the internet today as it was when first posted. What the internet does not reveal are the travails experienced by the college's maintenance teams, administrators, educators, students and other people interested in and/or involved with management of these GR installations. Some of the TESC installations have failed often enough, for a variety of reasons, that they were replaced entirely with "cool" (white) roofing membranes—the leading competition.

Many GR failures are driven by issues that would be a challenge to overcome without sustained and collaborative marketing efforts. However, the disconnect with consumer's needs may also be furthered by municipalities and sustainability certification programs committed to GRs by incorporating them into codes and standards. While competitive commitments to become "the greenest" or the "city with the most GRs," may have kick-started early adopters and various degrees of GR industry expansion, the industry may be enabling a pattern of failures that are difficult to overcome without the aid of further incentives and /or undesirable regulation.

Pre- and Post-Project Management

It may be beneficial to look at the overall framework into which the GR industry has evolved. The author values the delineation of individuals and specialists highlighted in Farnsworth's 2007 illustration of GR project teams in Figure 19 because it so accurately points to the landscape architect as a primary facilitator of today's GR project development. Comments were provided by five surveyed GR experts indicating their concern with this keystone position,

"…because it places too much power in the hands of a sometimes inadequately experienced landscape architect" or to another individual who may not be willing to delegate authority to appropriate external entities. Many professionals in the GR and general landscape industry are concerned that too much responsibility for GR outcomes is derived from landscape architects coordinating projects who are unfamiliar with the "Rubik's Cube" of plants and horticultural dynamics, if not other aspects needed for effective GR design.



Graphic by Craig Farnsworth (Hitchcock Design Group).
Modification using ovals with permission

Figure 19. Green roof project members.

Bold single-dashed circles in Figure 19 highlight the entities potentially involved with post-installation GR management, when the owner (in the solid oval) becomes the sole GR contact and/or the locus of management decisions. The double dashed line indicates currently limited but beneficial interaction between regulators or, better yet, consumer advocates and educators, who are involved with, but separate from the economic influence of regulators, and who can see to the long-term function of the GR from a balance of all perspectives. This is a missing alternative that separates the long-term objectives of regulators (also needed by the environment) whose need for stormwater management may, in the long term, supersede limited understanding and intentions of owners and/or the pre-installation GR planning team**.** Owners also need an advocate who is not necessarily going to try to sell them something they may want (but don't always need or have the skills to manage for the long term). Consumer advocacy may be a missing link that utility agencies can provide. The Landscape Architecture Foundation's pursuit and disclosure of long-term project data revealing all aspects of project difficulties, as well as project accomplishments and secondary effects may also help to counter this issue.

Development of professionals and technicians who manage GR installations and who have a broader familiarity of horticulture appears sensible, as suggested by leading GR professionals. European and other GR industry proponents with experience in restoration of failed GRs suggest field apprenticeship with one or more qualified GR mentors (a minimum of two years, according to one). This is in addition to product and theory-based trainings provided to people pursuing certification status via the Green Roofs for Healthy Cities organization (personal communications, J. Breuning, December 17, 2016; P. Carey, October 29, 2016).

Portland's ERs exemplify a design standard that may become an objective to achieve in a resource-limited future. Ongoing tours and research regarding details that enable ERs to function on fewer resource inputs could be sought by agencies that need to promote such a standard. Increased consumer advocacy could also consist of agency-operated information lines and demonstrations where consumers can visit a range of ERs and GRs and discuss GR issues with qualified individuals. Similar to the computer trade's on-line assistance, resources addressing GR-related horticulture and GR-related topics would help. Establishment of GR advocates by utility agencies would further enable customers to locate resources without the process becoming an automatic market proposition.

Elemental to the Paradigm

> Self-criticism is one of the earliest casualties in industries that are new and popular. Ecological consciousness requires this, however. One of the flaws in perceiving and accepting green roofs, living walls, etc. is in allowing one set of values to dominate the discourse. In a word, "capitalism." For example, if there is a monetary value, civic or personal, in a green roof, then it is valued. Saving energy, lengthening the lifespan of a roof membrane, saving money on storm water infrastructure, etc. In an economic environment where buildings get flipped every four to five years, this 75-plus-year commitment to a green roof gets weakened, and long-term benefits get ignored in favor of short-term economic gains.
>
> (*personal communication, P. Carey, October 29, 2016*)

People within the GR trade see rooftops as a "final frontier" in roofing, commercial landscaping and green architecture (Peck, via Cantor, 2008). By way of persuasive literature that often overstates consistently achieved benefits, the GR industry facilitates the continued experimental installation of a burgeoning variety of GR and other infrastructure products and approaches. The cost for this experimentation, in the form of incentives, that result in a small percentage of GR failures, is provided by rate-payers of agencies that need GRs as an aspect of infrastructure to provide stormwater and/or energy ecosystem services. The cost of GR failures is also eventually borne by the GR trade in the form of lackluster sales. The rest is shouldered for the supposed lifespan of each GR by owners, and by the environment. Parsing out the percentages of cost carried by each interest might be a valid research endeavor.

The creation of jobs associated with GRs is considered a benefit that is meant to reinforce a favorable perspective of the GR industry by policymakers (GRHC, 2015). The task of feeding a pool of not just trained or certified individuals, but people who are committed to the trade is made difficult by a high turnover rate of employees and the tendency of this landscape-related industry to be composed of people with potentially limited education and/or language barriers. Unenforced, unlicensed, unskilled, and uncertified people can also bring to the trade their own approaches to GR maintenance, which can also undermine intended sustainable outcomes. However, the landscape architecture and GR industries are in the best position to feed the community of qualified people to design, consult, *and* maintain what could be and has been built. They can do more to support both enforcement of qualified industry representatives and pursuit of data collection.

Infrastructure data development for asset management. Lack of data is the primary missing link that disables verification of green infrastructure systems currently promoted by utility agencies. While agencies cannot, by law, divulge the identity or contact information of current GR owners to independent researchers, they can supplement and analyze data gathered for in-house analysis. It is, however, somewhat understandable that smaller agencies cannot or do not consistently maintain such detailed records regarding GR and green infrastructure installations for which they may have provided incentives because of the potential costs involved for rigorous and replicable research. Consortiums of infrastructure agencies, however, can collaborate to gain discounts for larger-scale analyses.

Where incentives enhance the installation of any technology, it also makes sense that the private sector will take advantage of the opportunity for gain. Litigation addressing municipal incentives for both green roofs and other GrIS highlight the issue by questioning whether or not public funds are being appropriately spent.

Implications of the Research

Availability of the Portland data was key to making the research possible, but also illustrates how asset management can be implemented within the realm of “green” infrastructure, the way it is employed for “grey” infrastructure. Two thesis surveys were successful in systematically establishing failure definitions representative of the GR industry and GR owners or their representatives, respectively. The survey of GR experts is intended to be continued to strengthen the definition of GR failure with additional expert input representing the broadest involvement of the GR industry. Similarly, the measure of GR failure and success can be tested and strengthened by applying the research in other locales world-wide to verify whether or not incentives benefit GR installation, and/or catalyze a certain amount of failure. Further confirmation of the failure categories among experts and among other case studies are important tests for the hypotheses established in the thesis.

A foundation of agency data, alone, however, is insufficient towards the enhancement of GR installations and GR longevity. In addition to failure data baseline, the following considerations summarize what the research highlights as GR industry gaps.

Representative Application of Failure Analysis

Figure 20 provides a summary of GR causes and failures. The fishbone, and failure mode and effects templates offered in Chapter 3 provide additional examples of failure analysis that can be applied to the GR industry to consistently measure partial, and total failures on individual GRs or among ensembles of GR installations.

Overview Analysis of GR Failures

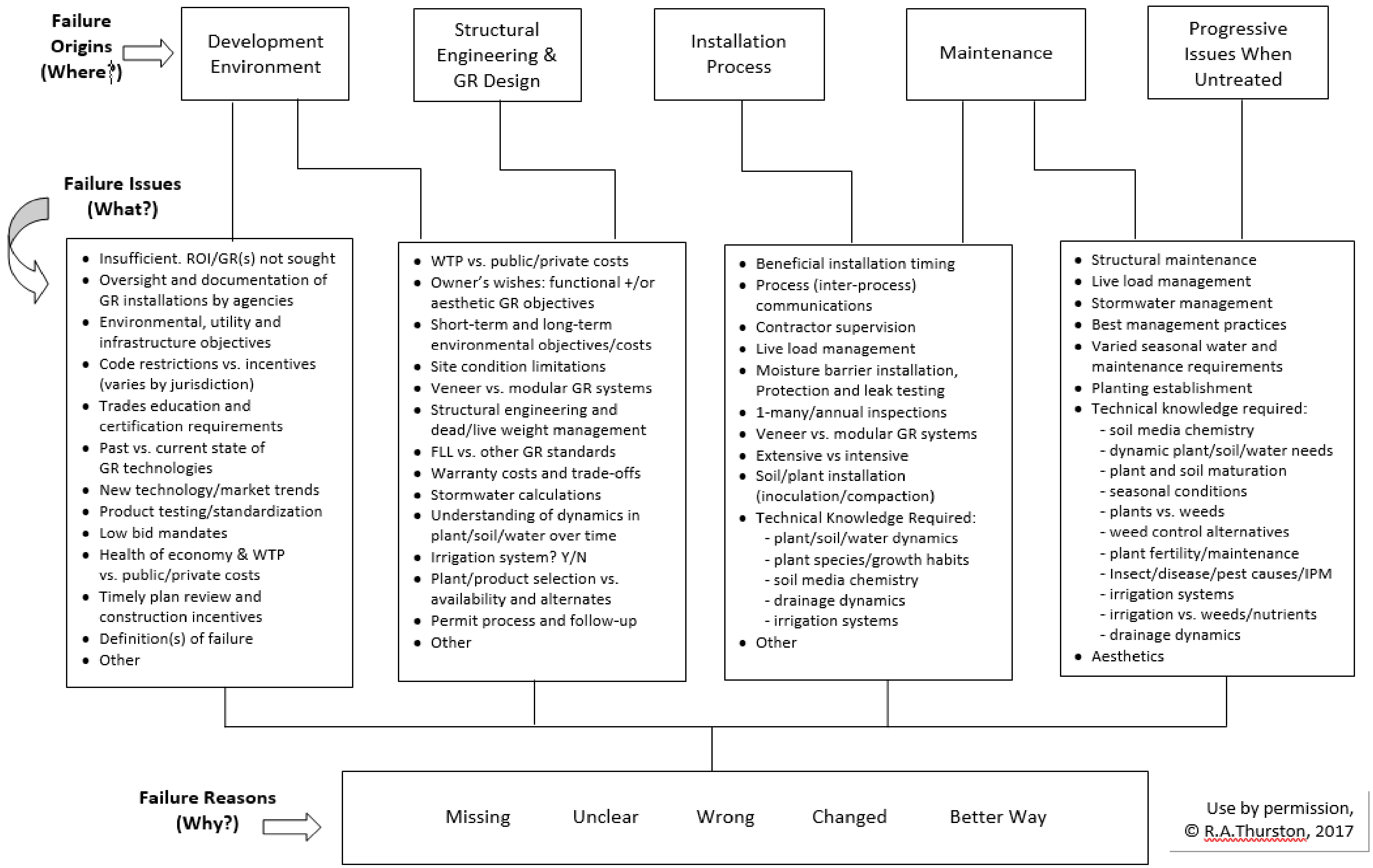


Figure 20. Green roof failure analysis (modified, as per Grady, 1996).

Applying "The Outside View"

Recalling the characteristics of major infrastructure described by Flyvbjerg (2009), (Chapter 3 – Failure Analysis by Other Industries), elements of project failure frequently include references to project risk, adoption of non-standard technologies, dependence upon community-designed and -built systems, expected evolution of projects and related community ambitions, plus the likelihood of unplanned events and related cost overruns, and misinformation that sometimes results from all of these details. All of these characteristics can be found among GRs in the Portland case study. This is not a surprise given the teamwork involved with individual and with programmatic GR development.

Different from political doubts that question the need for certification of landscape architects and GR professionals as central facilitators of GR installations, this consideration suggests instead that a higher standard of practice be placed upon such keystone team facilitators. Asking a landscape architect to design and coordinate the installation of a rooftop ecosystem without specific experience and knowledge of plants and ecology, in particular, is otherwise akin to asking an architect to build structures without knowledge of the building materials they are using. Lack of horticultural or ecological familiarity may not be the limiting factor, however. Regardless of the limitation, this role is reasonably limited to the front end of any project and cannot fully address the outcome so dependent upon the owner who adopts the finished installation. This is where the agency role as not just a provider of incentives is needed, but also the role of consumer advocate – if not on behalf of the consumer, on behalf of the agency's GrIS interests. To the degree that infrastructure expansion is needed, agency self-advocacy is needed in the form of asset management.

While the benefits of GrIS and GRs may be initially hard to quantify, we can't address the need for true asset management unless measurements over time are pursued. Lacking failure measurements specific to GRs, the thesis questions also apply to other GrIS incentive programs that aim to reduce environmental impacts, prevent erosion, protect water quality, preserve wildlife habitat, and decrease infrastructure costs. Because GRs and similarly functioning private installations provide needed public infrastructure benefits via ecosystem services, they deserve the same kind of asset management analysis that centralized brick and mortar operations already receive.

Beneficial Outcomes of Failure Analysis

> I have yet to work on a problem-free project and personally, I think it's critical for the industry to be aware of challenges so that the field can progress. We learn more from failures than successes. If there aren't failures, then the field isn't pushing boundaries. A certain amount of failure is critical, but it's important to manage the awareness so the perception is proportional.
>
> (personal communication, R. Garcia, February 24, 2016)

Failure is not necessarily a permanent outcome, but one that can generate useful information. The literature review in Chapter 3 provided examples of industries that look to failure for enhancement. Failure analysis, as employed by aerospace, medical, computer technology, and vehicle safety industries, demonstrates that failure analysis can aid GR stakeholders in reaching their respective objectives. Academic and business-oriented resources were similarly used to address economic and psychological aspects of GR marketing that influence pursuit of public and private GR benefits, and avoidance of failure. Awareness of these influences increases achievement of a broader range of desired GrIS and GR industry outcomes.

The thesis uses these guides to begin the work of self-evaluation on behalf of the GR industry. Survey responses from GR experts then provide perspectives of representative interest groups in defining GR failure, whose responses build a foundation of defined failure criteria. Additional perspectives from ICI GR owners, managers, and representatives provide real world context. Owner and manager input confirms and re-frames the variety of potential benefits. Reports and media highlighted outcomes either buff or tarnish the appeal of GRs that influence consumer WTP, or shrinkage of the GR industry. Cost and risk feedbacks further influence the outcomes for the GR industry and agencies that need GRs for GrIS expansion.

Implementation of failure analysis before future failures occur allows approach to increasing complex undertakings. In the short term, changes can occur that benefit individuals within the overall GR community. Over the long term, failure analysis and adaptation allows the industry to better meet the needs and benefits that agencies, GR owners, educators, and industry representatives indicate they seek. The thesis provides examples of GR performance analysis, as well as enhancement of incentive program implementation. Different aspects of the GR industry would benefit from application of failure analysis in the following ways:

Failure analysis enhances green roof planning and design. GR experts see design deficiencies that manifest in unmet "intentions" as the second most common cause of catastrophic and partial GR failures. Aside from specifications that overlook aspects of a GR as a functional protection of the roofing membrane, owner interests in safe access, simplified maintenance, and year-round aesthetics are areas of partial failure that tend to be ignored or oversold by public agencies and industry representatives. Failure is also common among GRs where inappropriate or untested plant species, media, and/or products are specified, or where design specifications fail to establish minimum protections of the roofing membrane during construction and long-term maintenance. Thesis findings encourage pursuit of not just one or two GR design objectives (as per the limited objectives of agencies providing incentives for GR installation), but that incorporate a balance of many intentions with which to actively achieve more of the benefits potentially provided by GR installations more frequently.

Failure analysis enhances green roof installations. There is overlap between issues associated with design and installation of GRs and potential failure. Leaks related to poor installation of membranes, drainage and flashing, or resulting from lack of membrane protection are noted among the most common causes of partial failure in conventional roofs and GRs. Team members involved with GR installation can be more vigilant in meeting minimally required specifications, more aware of potential problems resulting from inadequate protection of roofing membranes during construction and GR installations, and learn from issues that develop throughout GR life spans. Consideration of low-bid alternatives are also worthy of development to minimize involvement by uneducated and/or unscrupulous players from participation in costly GR projects. Everybody, except lawyers lose when they are allowed to play. Failure analysis would reduce what is known as "LEEDigation" resulting from consumer grievances associated with perceptually unfulfilled outcomes and catastrophic GR failures.

Failure analysis benefits GR owners and maintenance providers. Similarly, there is a correlation between GR design and installation and GR maintenance. Many of the issues in the maintenance category are also associated with sometimes unrealistic owner expectations of aesthetics and/or customer awareness of what is required to manage a GR, including any customer's ability to fulfill long-term GR maintenance requirements. Overselling of GR benefits and/or aesthetics to a possibly overconfident customer ranks among the primary complaints associated with partial GR failure among owners and managers.

Failure analysis benefits the GR industry. Viewing failure through a lens of opportunity supports beneficial evolution of the GR and other GrIS industries. Beyond the competitive measure of area or number of GR installations, the GR industry is not effectively measuring the rate of GR success. A systematic baseline and more uniform definition of GR failure enables development of improved approaches that overcome the currently limited installation rate of

GRs. A failure analysis baseline that illustrates correction of GR products and related approaches can start to provide evidence that GRs are truly beneficial, cost-effective, inspiring an increase in the public's WTP for the long-term benefits GRs can provide. In addition, rather than choosing short-term and less sustainable options, marketing of GRs that acknowledge trade-offs of potential GR benefits may increase interest from early adopting consumers who set trends via their trust in organizations that provide transparency and self-development.

Such a paradigm shift is, dependent upon the development of people charged with minimizing GR failure through enhanced GR planning installation and, increasingly important, long-term maintenance—with or without the aid of long-term irrigation. (Over)commitment to or negligence in the care of new technologies by consumers, reinforced by eager trade representatives and inadvertently by agencies, via incentives, comes with the consequence of GR failure in its myriad forms.

Failure analysis benefits public agencies and green infrastructure. Failure data inform and reinforce the justifications of agencies that rely on the ecosystem services of GRs (and similar GrIS) in their expansion of wastewater and energy utilities. Standardization of data gathering and failure analysis would also minimize policy litigation regarding perceived intentions of public programs. Without a failure baseline, agencies cannot measure the effectiveness of publicly paid incentive programs (Eisenberg et al., 2009).

Standardization of products and services might also minimize variance in outcomes, but it is an option fraught with difficulty in North America given dynamic climate variations, the variety of viable plant and media sources, and the large scale of the market. The region currently appears untapped by horticultural entrepreneurs, if not the larger roofing industry that needs to incorporate horticulturalist into its ranks. Reasons behind this lack of market saturation, however, may have more to do with homogenization of products by non-specialty interests.

Failure analysis supports climate change adaptation. Although currently limited, GRs and GrIS can contribute to a more positive outcome of climate change. GR industry, academic and industry educators, and municipal utility personnel play an important role in making the contribution possible. Failure analysis ultimately supports consistently successful GR installations that truly enable climate change adaptation. The endeavor is not just about GR or GrIS jobs and products sold, but also about success in adapting to climate changes becoming manifest without significant losses to motivate it. While failure is typically not anyone's objective, the environment upon which humans are dependent indirectly inherits the fallout of GR failures, including a lack of GR installations associated with consumer reticence based on risk and rate of ROIs (Gill et al., 2006). If consumer perceptions and concerns are addressed, how many more GRs could be installed than are currently? Failure analysis provides all stakeholders with insights and feedback, while gaining both consumer trust and a broader range of the benefits that GRs can (but do not always) offer.

As a representative of both the landscape design consultant and agency interests, and a sustainable infrastructure agenda, Raphael Garcia of the San Francisco Public Utility Council offered the following comment, which encourages the GR industry's pursuit of excellence, while continuing the incentivization of GRs overcome the public's un-WTP, especially when benefits enjoyed by others than the owner, is limited:

> As long as we design projects to solve problems of today, we'll never be able to solve the problems of tomorrow. Green roofs are a great example of trying to solve the problems of the present and future but require additional investment. Some see green roofs as a luxury, but even if that's true, now is the time to invest in the future while the economy allows these types of investments.
>
> *(personal communications, R. Garcia, February 23, 2016)*

How the Research Can Be Extended

Continued development of the operational definition of GR failure and its application aids all of the interest groups identified herein. Having established a process for data collection and failure analysis may encourage other municipalities, in collaboration with the GR industry and educators, to pursue it. The time needed to enhance GRs and other green infrastructure technologies depends upon data-gathering capacities of agencies in league with educators, and the industry alike. The failure definitions provided in this thesis provide a baseline from which further assessments can be replicated and compared. Objectives established in the thesis are achievable among other GrIS systems.

Research that Extends or Tests the Thesis

In-situ performance analysis and a review of industry literature known to address sustainability might follow (as per McDonough & Braungart, 2002), but individual and collective program analyses need data baselines, like the one established herein, against which to compare change. Next in line would be the type of "innovation and smart project design" suggested by Zimmerman Roth and Partridge (2017) that catalyzes such analyses toward success. LCCA analysis that compares the similarities and difference of ERs with GRs would also be beneficial to this evaluation. The continuation of GR project investment ultimately enables creation of replicable answers and GRs worthy of the inheritors of our present practices.

The need to establish a representative definition of GR failure, as well as GR failure rates that overcome regional climate and economic variations, also suggests the need for the following:

- ❑ Statistical review of "panel" or longitudinal data of property owners and managers, considering their perspectives from the starting point of interest in green infrastructure to post-installation at two-year intervals until the installations are considered mature at four to 10 years or later.

In addition to verifying the baseline of failure in GRs, research of GR failure-related covariates would also identify the practices and products that make or break perceived success of any GR, as determined by the owner. It would further distinguish whether location and climate variations are significant factors in GR success and failure, which may then also correlate to enhancement of specific products, applications, and/or maintenance approaches.

- ❑ Failure definition input from a minimally statistical or greater representative sample of GR experts in all representative categories of the GR trade.
- ❑ Implementation of owner/manager surveys in additional municipalities where the rate of GR installations is notable to facilitate effective development of standardized GR asset management. Target municipalities within the U.S. should include Chicago, New York City, San Francisco, Seattle, Philadelphia, and Washington DC. From a global perspective, Basel, Switzerland; Toronto, Canada; Mexico City; Melbourne, Australia; Hong Kong, China; Tokyo, Japan; and one or more cities in Germany and England all stand out in the literature and would provide important market comparisons for added context.
- ❑ Marketing research that examines how other industries have navigated transitions from pre-failure analysis to post-definition and engagement of self-evaluation. This might include a measure of the payoffs in terms of industry growth. Emulation of the more successful strategies may provide the profit margin incentives that will fuel a similar pursuit within the GR and other GrIS trades as they seek to become marketable, if not more sustainable.
- ❑ Measuring a more representative population of owners regarding their perceived fulfillment of intended GR objectives would allow consumers to gain a much more effective risk assessment and cost-benefit analysis than the independent performance studies currently undertaken.
- ❑ Owner tax and real estate data are accessible through public records requests. Better would be automated collection of relative real estate, tax, and property values over a pre-identified period of 10–20 years to correlate rates of return within communities identified by participating municipalities to provide additional ROI insights to consumers and public agencies targeting effective incentives.
- ❑ Increasingly importantly, who is responsible for encouraging and paying for the consumer education and applications that make GRs more sustainable?

Questions Related to, but not Addressed by the Thesis

- ❑ What is the relative contribution of GRs to the overall choice of GrIS options, and are the benefits worthy of greater or lesser incentivizing?
- ❑ Given the potential benefits that GRs offer, is there a way to plan and implement GRs that more consistently acknowledges more environmental objectives?
- ❑ How many GRs installed have, without one or many issues, fulfilled the promoted design objective(s) at the stated cost, without negatively affecting the environment beyond the installation?
- ❑ How many GR installations have encountered difficulties requiring litigation?
- ❑ When GR removal from structures is required to repair membranes, how often are they fully replaced?
- ❑ How might utilities best follow and track the changes that occur among the GRs in their collective GrIS systems?
- ❑ When GRs or, worse, the roofs beneath them, fail, what and how much are the costs, and who pays them?
- ❑ When GRs or, worse, the roofs beneath them, fail, how does one determine who is responsible for the failure liability (without litigation)?
- ❑ If COP/BES imposed an eco-roof-only design and maintenance limitation, would citizens and investors still install them?
- ❑ Cost benefit analyses comparing the relative benefits and trade-offs of GRs used for enhancement of stormwater infrastructure vs. energy infrastructure.
- ❑ Which of Portland's older buildings are truly available and cost-effective roof space for GRs installation?
- ❑ What influence does media play in the influence of consumer pursuit of GRs outside of media produced by the GR industry?
- ❑ By what methods might GR failures resulting from required low bids, be minimized?

Other Unknowns about Green Roof Failure

In addition to statistical calculations of the issues contributing to GR failure, additional research is needed to determine costs associated with GR failures, including the environmental cost externalities that GR failures represent. How much, for example, does it cost to put a GR in a landfill, beyond the service to do it and the replacement of membrane once the GR has been removed? What is the cost to the public for having that much less space available in the landfill where the GR was wasted? Considering the costs of landfills and public aversion to them expressed through NIMBY outcries, externalized cost of wasting GRs could be high and add to the GR failure math that needs to be fully calculated.

Conclusion

By way of failure, the thesis examines the relative success and failures of GRs as a choice among many GrIS options so far applied to manage urban stormwater. The failure rates defined and established here support application of asset management for on-going evaluation of GRs. The framing of GRs and their failure as a niche technology within the realm of GrIS invites consideration of establishing similar operational definitions to be used for all forms of GrIS, especially including, permeable pavements, bioswales, and LID.

Green roof failure, at its most basic level, includes structural collapse or GR removal, but what about all the roofs that fail to meet their designed "intention(s)"? There are many shades of grey, which reflect a wide range of consumer intention and environmental drivers. While the rate of GR failure may be declining, and may now be situated below 10% in many cities, the rate of market penetration of GRs remains below 5% in most North American municipalities. GRs in North America, more than in other parts of the world, are not only promoted by utility agencies and industry representatives, but their installation appears superficially to associate with economic trends. After nearly two decades of incentives and public educations the low market penetration values are an indicator that, even without the aid of this thesis, tells us the GR trend may be passing, and/or that a history of GR failure influences future consumer participation. Market penetration is as important a measure as the numbers of GRs installed (and sometimes uninstalled at later dates).

GRs represent a small proportion of the GrIS market, which is potentially undermined by consumer responses to cheaper (white and brown roofs) or newer technology trends. Although statistics suggest GR installation has increased over the years, the values promoted are misleading. And while the list of benefits provided may be growing, the tiny niche that GRs currently occupy provides important but only trivial amounts of climate change benefits. There is some benefit to competition in support of the GR trade and/or GI certification programs, but it belies the real need to purse extensive installation of GRs in the interest of amelioration of human development and climate change scenarios.

Compared to the lack of GR data when GR incentives were first promoted in North America, enough data now exist to overcome the inability of municipalities and the GR industry to clearly define and self-assess GR failure. With or without an operational definition, no prior research addressed the rate of green roof failure in any type of structure. The more notable failure could eventually be not just the lack of failure definition, but the lack of will to address challenges that self-examination by the GR industry and its advocates represent.

Regaining Ground. Thankfully, failure is not a permanent affliction. However, if climate predictions are even vaguely accurate, the potential for future losses could be increasingly catastrophic (Intergovernmental Panel on Climate Change (IPCC), 2012). Humans, and other life forms upon which humans are dependent for survival, need not just economic results, but a streamlining of functional results providing benefits that the tiny niche of GRs and other GrIS are said to assist. Important among these are carbon sequestration, UHI reduction, habitat restoration, and the stormwater management benefits that are listed within this thesis. Let us use the baseline of failure discerned by members of the trade to apply its collective genius toward GRs that last as long as the industry says they should. Let this approach keep GRs from becoming eroded or turned into landfill before the lifespan of the membranes beneath them is truly worthy of recycling or some other form of reuse.

Municipal utilities interested in the benefits GRs can provide play an important role in the provision of effective incentives and consumer advocacy, plus enforcement of GR BMPs that minimizes GR failure. Provision of consumer education, and unbiased maintenance guidelines would help overcome consumer disenchantment and trepidation. Such advocacy needs to address not just ROIs, but also aesthetics, and maintenance.

There is a particular need to more effectively address the long-term management of GR installations. Where owners don't participate, utility agency provision of maintenance might prevent the partial failures shown to synergize into total, or otherwise catastrophic failures—or the preference for other roofing alternatives that don't offer the benefits that GRs can (but don't always) provide. A horticulturally informed approach might also address consumer and contractor beliefs about BMPs that work and how local actions can impact the environment well beyond the edges of one's GR. Numbers-driven interactive involvement in processes that limit the continuous need for landscape inputs is ultimately more effective than a competitive count of installations.

Addressing what appears to be minimal implementation of GRs in North America after nearly two decades of incentives suggests all interests make a paradigm shift that incorporates the analysis of failure. This thesis establishes a roadmap to how GR failure analysis can be implemented, the measures it begins to provide, and the differences of failure criteria that are currently unaddressed. The last considerations in Chapter 5 look at the context in which this shift could occur, the communications among the interest groups identified that exists but might consider alternative, or refreshed approaches, and the variety of data models that could be used and improved upon to make it happen.

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Professional Resources

In addition to professional contacts among GR experts made via thesis surveys implemented, follow-up communications provided additional insights. The following individuals made major contributions to the clarity of the author's understanding of GRs and their potential for failure:

- **Jörg Breuning**: Knowledge gained from early industry certification and 36 years of hands-on education and experience, in addition to GR contracting since 1985 with specialization in GR failure resolution. Breuning's familiarity with German GR practices and the Forschungsgesellschaft Landschaftsentwicklung Landschaftsbau (FLL), a.k.a. German Landscape Development and Landscape Research Society standards (2008), inform his understanding of GRs and their failures. His pragmatic analyses of GR failures and relentless advocacy for an enhanced GR industry make him similar to Ralph Nader, who enabled passage of landmark legislation providing numerous consumer protections in the United States. Breuning strives for unified GR products and minimum training standards. Although not peer-reviewed, Breuning's GR information blog and personal insights are among the more important sources of thesis information.

- **Patrick Carey**: A 17-year history of first-hand involvement within the GR trade provides a foundation for Carey's GR knowledge and interests. Carey was originally involved as a volunteer with Seattle, Washington's initial GR installation programs via the NW EcoBuilding Guild. There he was invited to explore sustainable construction while expanding the market among commercial and residential interests. Carey has also been involved as an educator and promoter of GRs through his affiliations with the GRHC and Virtual Summit broadcasts coordinated on behalf of the organization Greenroofs.com.

- **Jon Crumrine**: Understanding of failure via tours of Portland and other regional green roofs was made possible by Crumrine, whose experience in the GR trade includes work as an employee of a variety of GR companies and, more recently, as an independent contractor. Crumrine's understanding of GRs is built upon 15 years in the trade (three years as a GRHC-qualified Green Roof Professional [GRP]), after having worked his way up to a range of knowledge in various aspects of the GR trade.

- **Tom Liptan**: Nationally known among GR professionals and program administrators, Liptan has been involved in the international GR trade and development of the GR incentive program on behalf of the city of Portland, Oregon, since 1996. He is said to be the first person to recognize the value of GRs as a tool to manage stormwater after installing and monitoring a GR on his own garage. Liptan is now retired from Portland's Bureau of Environmental Services (COP/BES) division, but continues to be involved with the establishment and use of incentives to promote GRs in North America (City of Portland Bureau of Environmental Services, 2013). Liptan was instrumental in providing initial GR contacts and issue insights for the development of this thesis.

APPENDICES

Appendix A:

GLOSSARY of TERMS

Glossary

Best Management Practices (BMPs): A business efficiency term connoting methods or techniques found to be the most effective and practical means to achieve an objective while making optimum use of available resources.

Blue roofs: An ancient and recently renewed technology similar to and sometimes used in combination with vegetation that maintains precipitation on roofs rather than allowing it to enter storm drain infrastructure (Roy, Quigley, & Raymond, 2014).

Brown roofs: This technology generally excludes pre-grown plant materials and provides stormwater abatement, but the primary objective sought by installing a brown roof is the creation of habitat for increasingly rare birds and insects (Blackdown Ltd., n.d.) and possibly also plant species that prefer construction rubble habitat.

Building Research Establishment Environmental Assessment Method (BREEAM): Developed in 1990, BREEAM offers more than 100 credits toward environmental assessment of buildings worldwide. Trained assessors weigh pre-completion site evidence against credit criteria and report their findings to the Building Research Establishment, which validates the assessment and issues certificates. Like LEED certification, the BREEAM program objective is to improve building design.

Climate change: Increasingly evident since the advent of industrialized society, climate change is a long-term shift in global and regional temperatures, precipitation, and wind patterns, among other effects that negatively affect human water resources, agriculture, power and transportation systems, and the natural environment.

Combined Sewer Overloads (CSOs): Under normal weather conditions, combined sewer systems (CSSs) currently operating in nearly 900 North American municipalities collect sewage, industrial wastewater, and precipitation runoff in single transmission pipes. The combined wastewater containing human and industrial waste, toxic materials, and debris, as well as stormwater, collects at treatment plants for removal of the waste before being discharged to nearby waters. During high precipitation events, the volume of wastewater can exceed CSS capacity. The result is a combined sewer overflow (CSO), which includes discharge of untreated stormwater and wastewater.

Cool roofs: Employed in Mediterranean climates for centuries, cool roofs employ reflective white roof coloration or white-colored roofing membranes to aid in the reduced absorption of solar energy that creates urban heat island (UHI) effects (EPA, 2008a; Santamouris, 2014). From a cost-competitive perspective, cool roofs are thought to provide simplified maintenance that puts them ahead of GRs in the short-term, but not necessarily in the long-term (Garrison et al., 2012; Sproul, Pun Wan, Mandel, & Rosenfeld, 2014). Life-cycle cost analysis would provide the most definitive assessment on a case-by-case basis because of all the variables involved. LCCA is currently being studied by other academics.

Ecoroof: Terminology used by the City of Portland, Oregon, Bureau of Environmental Services (COP/BES) to define a type of "low-maintenance" green roof providing externalized infrastructure via ecological services, such as stormwater retention, filtration of precipitation, and habitat for insects and birds (Spolek, 2008).

Ecosystem services: Non-produced natural system assets via provision of food and filtered air and water; climate and disease regulation; and support of nutrient system recycling and pollination in league with recognized cultural (spiritual and recreational) benefits. Ecosystem services are beneficial externalities relied upon by humans, but only since the turn of the century have these assets been assigned economic values.

Relative to the thesis, GRs provide externalized ecosystem service benefits to municipal utilities in the form of stormwater management and the extension of grey infrastructure. Similarly, GRs provide private benefits in the form of aesthetic benefits associated with health and productivity (James, P., Hart, J. E., Banay, R. F., & Laden, 2015), and sometimes increased property values (Ngan, 2004)

Environmental externality / Externalities: A term used by economists that defines the side effect(s) or consequence(s) of human industrial or commercial goods or services that positively or negatively effects environmental interests without the full cost being reflected in the cost of the goods or services billed. The cause(s) may be created by numerous entities that are difficult to regulate.

Untreated stormwater pollution resulting from release of vehicle particulates in air and water is an example of a negative externality that affects water bodies, especially in built-up urban areas. Relative to green roofs, the cost for incentives provided to interests that install rooftop vegetation is an externality. So, too, are the costs to maintain a municipality's grey and green infrastructures, regardless of how well the infrastructure fulfills its respective objective service. Stormwater treatment is financed, in part, by externalized rates paid for by all property owners within the stormwater utility's service area, whether or not property owners are the source of the pollution.

The typically non-monetized value of insect pollination is often cited as an example of a positive externality in that the service has, until recently, been provided by nature at little or no expense. The cost of this invaluable and potentially non-replicable ecosystem service is increasingly reflected in rising food costs.

Evapotranspiration (ET): The vaporization into the atmosphere of water from soil surfaces, and from respiring plants. Use of ET is one tactic enabling the cooling service of GRs.

FLL guidelines (FLL): The outcome of the German Landscape Research, Development, and Construction Society, an independent nonprofit organization founded in 1975. The guidelines include GR planning, installation, and maintenance and review current German GR technologies. FLL is considered the leading global reference for creation of reliable and high-quality green roofs (Philippi, 2005).

Grey infrastructure: Relative to stormwater, grey infrastructure comprises conventional, centrally managed single-purpose drainage and water treatment system assets composed of pipes and pumps that convey urban stormwater away from built environments. Sometimes the stormwater treatment system is combined with the sewer treatment system that is vulnerable to combined sewer overload (CSO). Treated water output is typically directed to downstream water bodies.

Green buildings: High-performance architecture using efficient energy systems and other technologies that provide healthier living and working environments by maximizing user comfort and productivity while minimizing environmental impact.

Green infrastructure (GrIS): Cost-effective management of wet weather runoff by using privately engineered and managed systems and resilient ecosystem services in public commons to move stormwater away from the built environment while minimizing overwhelm of grey infrastructure systems and creating secondary benefits (i.e., aesthetics, air filtration, habitat, etc.). Green infrastructure treats stormwater at its source while providing additional environmental, social, and economic benefits and includes green roofs, rain gardens, green street treatments, Light Impact Development (LID), and other ecosystem service system technologies.

Green roof: Among the broadest of terms used to reference the variety of growing media and vegetation and drainage systems installed on top of structural membranes found on building rooftops. See Chapter 2 for a detailed overview of green roof history and technology options.

Green Roofs for Healthy Cities (GRHC): A member-based nonprofit industry association dedicated to development of the North American and worldwide green roof and wall industry providing GRHC-defined best management practices, industry advocacy, annual conferences, consumer referrals to accredited professionals, project performance marketing overviews, awards, plus training and accreditation. Publications overseen by the GRHC include:

- ❑ The quarterly *Living Architecture Monitor*® (LAM) publication, regarding emerging industry research, design, manufacturing, and policy activities.
- ❑ The quarterly *Journal of Living Architecture* (JOLA) publication, referencing peer-reviewed scientific research.

Heuristics: A decision-making approach based upon minimal information, preferred because of the limited thinking required. Alternative information-rich “systematic” solutions require more thought involvement and potential debate. Heuristics are empirically shown to better persuade behavior conversion. However, the outcomes can prove worse than the original problem being resolved because insufficient decision-making information has been provided or is purposefully limited.

Infrastructure: Networks of built public and/or private assets that provide energy, sewer, water, transportation, shelter, and other necessary community-wide services. These relatively permanent capital fixtures have extended lifespans of one to five decades and are typically managed by municipal entities that provide semi-annual evaluations and repairs for the duration of the asset's useful lifetime.

LEED: Leadership in Energy and Environmental Design (LEED) is an internationally recognized building certification system developed in 1993 by the United States Green Building Council (USGBC). The points-based strategy provides third-party verification of voluntary building or community design and construction using high-efficiency systems for reduction of energy, water, CO_2 emissions, and improved indoor environmental quality, as well as stewardship of natural resources. LEED "certified" structures confer symbolic and economic benefits to their owners, including increased real estate values; liability reductions; utility savings; and opportunities to obtain incentives, such as tax credits or permit allowances. While LEED does not require training, credit is gained if an Accredited Professional (AP) helps gather pre-completion certification evidence and advises participants. Evidence is submitted to the USGBC, which issues tiered project certificates. Like BREEAM certification, the ultimate objective is to improve building design.

LEEDigation: A term that references litigation taken up by owners and tenants of LEED-certified buildings whose LEED project expectations were not met.

Life-cycle costs: These costs include direct and indirect values of purchase, development (including all aspects of planning, and permitting), operation (including short- and long-term maintenance and renewal), disposal (including planning for, deconstruction of, and waste storage fees), and environmental costs (fees externalized through shared costs, or otherwise historically discounted from having not been assigned a monetary value).

Living Building Challenge: This international certification program was created in 2006 and encourages use of green building methods and components among new residential and commercial development. Originally developed and implemented by the Cascadia Region Green Building Council, a subsidiary of the International Living Future Institute, and associated with the Canada Green Building Council and U.S. Green Building Council. Compared to BREEAM or LEED certification programs, it is considered more rigorous because it is built upon standards that advocate for social and ecological justice. Stormwater capture is one of many standards required by the program.

Native plant: A plant which, over thousands of years, has co-evolved and formed complex symbiotic networks with animals, fungi, and other soil microbes. Representing one cornerstone of biological diversity considered important to human survival, native plants are also thought to provide the best food and shelter resources for regionally native wild insects, birds, and other animals. Survival of native plants is sometimes limited to the ecosystems in which they grow. Their loss can undermine the symbiotic relationships between dependent plant, soil microbe, and animal species while also undermining development of useful human food, medicine, and industrial products.

Stormwater: Water that originates from precipitation events including snow and ice melt. Stormwater can soak into the soil (infiltrate), be held on the surface and evaporate, or run off and end up in nearby streams, rivers, or other water bodies (surface water).

Sustainability: Framed from the business perspective, sustainability refers to management of the triple bottom line, a process by which companies manage their financial, social, and environmental risks, obligations, and opportunities (or profits, people, and the planet). Framed from Herman Daly's ecological perspective, it is the ability to continue a defined behavior indefinitely (Daly, 2005). This approach endeavors to maintain the capacity of the planetary biosphere to meet the needs of the present generation of humans without hindering future generations from being able to meet their needs.

SWOT: A structured evaluation approach that builds upon the acronym derived from analysis of Strengths, Weaknesses, Opportunities, and Threats.

Urban heat island (UHI): This acronym is used to identify elevated temperatures experienced in metropolitan areas that are caused by structural and pavement absorption and re-release of solar energy mixed with vehicle emissions.

Vegetated roof: An interchangeable term for ecoroof or green roof (GR), indicating the installation of plantings on roofs of structures for the sake of achieving up to twenty public and private benefits.

Willingness To Pay (WTP): An economics term conveying the maximum amount an individual is willing to sacrifice to procure a good or avoid something undesirable.

Appendix B:

SURVEY #1

Survey Instrument #1

DEFINING GREEN ROOF FAILURE

A Questionnaire for Green Roof Specialists

Because of your role as a green roof engineer, designer, provider, and/or as a policy agent involved with green roof systems and their installation, you have been identified as a qualified person to complete this 10–15-minute survey. Your participation in the survey helps to build an operational definition of green roof failure(s). Understanding green roof failure enhances the design, installation, and maintenance of future green roof systems. It also addresses incentive programs that support green roof installation. Your responses ultimately support long-term promotion of the green roof industry, in addition to enhancing the benefits that green roofs provide to humans and to the environment.

Please note that your voluntary completion and return of this survey represents consent for me to incorporate your responses into a master's thesis, which will employ the green roof failure definitions being developed via this survey.

This information will not be made public, sold, or shared in any way. The data generated from this questionnaire will be made public, preserving the anonymity of individual responses. Should I wish to quote you, I will contact you to verify your comment(s) and to confirm your consent. For this reason, it is important that you provide your contact information.

Please complete your survey by Monday, February 29, 2016.

If you have additional thoughts about green roofs, please contact me by phone at 253-227-4923, or by e-mail at thurut04@evergreen.edu. Thank you in advance for your contribution to the green roof industry!

(page 1, above)

(page 2, below, and continued, next page)

Issues that Define Green Roof Failure

Q1. In your own words, please provide a general operational definition of green roof failure.

Q2. From the following list of issues often associated with green roof design, installation, and maintenance, please click on one box per row to indicate the role each item contributes to green roof failure. Would you say the issue is: Not an Aspect of Failure; A Potential Failure if Left Untreated; OR, An Actual Failure?

	Not an Aspect of Failure	A Potential Failure if Left Untreated	An Actual Failure
• Plants "wander" from original planting location(s)	○	○	○
• More than 25% of the plants require annual replacement (non-food greenroofs only)	○	○	○
• The appearance of plantings in dormancy or "off-season(s)" is unacceptable	○	○	○
• Planting substrate fails to retain 30% or more of average rainfall	○	○	○
• Poor/no substrate drainage (substrate is below drainage outlet, plants drown)	○	○	○
• Soil substrates clog storm drainage system(s)	○	○	○
• Soil substrates have eroded too rapidly	○	○	○
• Greenroof plantings require irrigation to supplement precipitation	○	○	○
• Potentially required nutrients negatively affect stormwater quality	○	○	○
• The greenroof leaks more than a conventional roof	○	○	○
• Greenroof leaks are impossible to locate/fix w/o removing installation	○	○	○
• Greenroof harbors weeds that damage roof liner	○	○	○
• Greenroof requires specialized maintenance staff to manage weeds	○	○	○
• Greenroof requires specialized maintenance staff to manage irrigation system(s)	○	○	○
• Greenroof harbors pests that damage protective roof liner	○	○	○
• Greenroof installation is too heavy for the substructure	○	○	○
• Greenroof leakage has permanently damaged the substructure	○	○	○

Other (please specify)

Q3. From the following list of issues often associated with green roof economics and the environment, please click on one box per row to indicate the role each item contributes to green roof failure. Would you say the issue is Not an Aspect of Failure; A Potential Failure if Left Unaddressed; OR An Actual Failure?

	Not an Aspect of Failure	A Potential Failure if Left Unaddressed	An Actual Failure
• Greenroof installation costs more than initially budgeted	○	○	○
• Greenroof impedes re-sale of property	○	○	○
• Greenroof increases insurance rates +/or limits insurance availability	○	○	○
• Greenroof reduces access to mortgage financing	○	○	○
• Greenroof return on investment fails to meet target	○	○	○
• Greenroof has a negative effect on property value	○	○	○
• Greenroof fails to moderate structure's internal temperature	○	○	○
• Greenroof fails to buffer external noises	○	○	○
• Greenroof fails to sufficiently exceed the lifespan of a conventional roof	○	○	○
• Greenroof fails to attract beneficial insects and/or wildlife	○	○	○
• Greenroof fails to filter air and/or water pollutants before draining	○	○	○
• Greenroof doesn't offer aesthetic benefits to building occupants	○	○	○
• Greenroof doesn't offer aesthetic benefits to building occupants	○	○	○
• Greenroof doesn't offer cooling benefits to building's neighboring climate	○	○	○
• Greenroof fails to sustain plant growth	○	○	○

Other (please specify)

(end of survey page 2, page 3 follows)

Green Roof Policies and Incentives

Q4. Which green roof incentives are offered by your agency, or by an organization that encourages pursuit of green roof installations in the location(s) where you do business? (*click all that apply*)

++

- [ ] No incentives are offered
- [ ] Incentives were offered at a prior time, but are no longer available (please list year(s) of incentive program in comments window, below, and check all incentive types that apply)
- [ ] Financial incentives (*please list values offered in comments window below*)
- [ ] Reduction of permit fees (*please list percentage or dollar value provided in comments window below*)
- [ ] Expedited permit process
- [ ] Increased construction +/or density allowances
- [ ] Incentives for public health-related installations
- [ ] Incentives for on-site agriculture

Other: (please specify)

Q5. Which green roof standards currently exist in your jurisdiction or region? *(click all that apply)*

++

- [ ] There are no greenroof standards here.
- [ ] Pre-completion inspection
- [ ] Post-completion inspection (*one only*)
- [ ] On-going post-installation assessment or inspection *(please list # of years in comments window, below)*?
- [ ] Minimum maintenance requirements
- [ ] Minimum standards for structural integrity
- [ ] Minimum rate of stormwater retention (*please list percentage of retention required in comments window, below*)
- [ ] Requirement to increase permeable surfaces (*on structure*)
- [ ] Filtration/capture of landscape fertilizers/chemicals
- [ ] Aesthetics / weed management standards
- [ ] ASHRAE standards for energy efficiency
- [ ] LEEDS ®
- [ ] SITES ®
- [ ] Energy Star ®
- [ ] Green Built ®
- [ ] Green Factor ®

Other/Comments (please specify):

Q6. In what ways does your agency or organization promote the installation of green roofs? (click all that apply)

- ☐ Education only
- ☐ Education plus other activities
- ☐ Certification of greenroof contractors
- ☐ Discounts on products and/or services
- ☐ Financial incentives
- ☐ Regulatory incentives
- ☐ None of the above
- ☐ Other (please describe in comments window, below)

Other/Comments (please specify)

(survey page 3, above; page 4, below)

GENERAL DATA – to be answered by the green roof specialist completing the survey.

Q7. In the window below, please provide a brief overview of how many years have you been involved with green roof design, installations, or incentives, as well as your areas of expertise.

Q8. Your Contact Information:

Name/Title	
Best time (w/ time zone) to reach you	
Address	
Address 2	
City/Town	
State/Province	-- select state --
ZIP/Postal Code	
Country	
Email Address	
Phone Number	

End of Survey

Survey #1 - Results

Question 1: Impromptu Definition Responses Provided by GR Experts

To derive an initial operational definition of GR failure, question #1 asks participants to "…*provide a general operational definition of green roof failure*." The posing of this question before seeking expert perspectives on specifics was intentional to solicit impromptu answers. Results are listed in Table 29, below.

Table 29.
Coded Ranking of Experts' Impromptu Definitions of Green Roof Failure (Survey #1)

Q1. Defining Issues Associated w/ GR failure (impromptu responses were coded)	**Rank**	**Count of Respondent References to Q1**	**Percent of Respondents Associating Concept w/GR Failure**
Vegetation	1	17	43.6%
Owner Designed Intent	2	15	33.3%
Poor Design	3	12	30.8%
Membrane Leaks	4	11	28.2%
Aesthetic	5	5	12.8%
Excessive GR or Product Maintenance	5	5	12.8%
Storm Water Function	5	5	12.8%
Weeds and Plant Biodiversity	5	5	12.8%
Amenity	6	4	10.3%
Lacks Habitat	6	4	10.3%
Planting Media	6	4	10.3%
Structure Fails	6	4	10.3%
Tolerate Climate	6	4	10.3%
Poor Drainage	7	3	7.7%
Temperature / Sound Insulation	7	3	7.7%
Weeds	7	3	7.7%
Economic	8	2	5.1%
Life Span of Roof	8	2	5.1%
GR Requires Replacement	8	2	5.1%
UHI	8	2	5.1%
Installation Damage	10	1	2.6%
Irrigation	9	1	2.6%

Survey Respondent Data Question 1

Question 1: "In your own words, provide a general operational definition of green roof failure."

1. A green roof fails if it does not meet the expectations of the owner. Those expectations could be for aesthetic appeal, stormwater management, biodiversity, economic, etc.). A failure for one roof may not be considered a failure for another roof.
2. Failure is a failure of plants to thrive so the stormwater function of the green roof system is unsuccessful. The green roof does not support habitat for insects and birds. Plants that are grown in non-green roof soil types fail or do not thrive and leave areas of failure. I think that much of the early failures are or can be resolved now through correct specification of soil and plants that are tested and appropriate. Green roofs in our climate need irrigation, if green roofs are not irrigated here they will fail.
3. Failure of drainage and underestimated structural capacity of the roof.
4. I would classify both moisture infiltration into the building and plants dying or not being able to self-sustain without a lot of maintenance a green roof failure.
5. The roof leaks, the roof is not GREEN (vegetation cover less than 100% after 2 years of establishment period), the roof is a monoculture or lacks biodiversity aspects (1-2 Sedum species as vegetation), the roof does not drain and floods, the roof has an ecological imbalance (e.g., grass species take over and die off in a hot summer), the building collapses (wrong weight calculation thanks god that very rarely happens)
6. Green roof failure is the inability for the selected plants to grow and thrive, and/or damage to the waterproof membrane or other structural damage caused by the green roof design or installation.
7. A green roof that has significant structural issues that necessitates removal or replacement of the entire roof.
8. Over 50% of original plants have died and has been taken over by invasive plant species. 2. Waterproofing membrane has delaminated and is allowing water under the membrane and into the facility. Either one of the above would be considered a green roof failure.
9. Either the water integrity has been compromised and/or the vegetated components are not performing as specified.
10. When the design intent of the product does not cater for a client's requirements, in terms of budget, product suitability for function (e.g., amenity, thermal/acoustic insulation, habitat creation, storm-water management, etc.), aesthetic outcome, durability, longevity, general functionality, suitability to/tolerance for climate and local weather, both in terms of hardware and green-life performance.
11. A failure would result if one of these three fundamental project objectives is not met: 1) ensure leak free waterproofing 2) ensure the structural integrity of the building is not compromised 3) ensure health and vitality of the vegetation.
12. Worst – structural failure; Bad – leaks; Next – soil or media failure; Next – plant failure

13. Not planned and thought true installation – design. To plan and install a good green roof it needs to think ahead what kind of vegetation you want to get (plant association, habitat etc..) – ecosystem approach.
14. The best extensive green roofs are those which replicate ecosystems (landscapes) on its surfaces, that means different local natural substrate types in different height, then you get a variety of plant species / associations.
15. Leaking of the roof under the planted surface or a significant die-off of plant material
16. Green roof failure is the inability of the system to recover from variable site conditions such as temperature, precipitation, pestilence, or lack of proper function of the composite layers.
17. A failure of any major component of the green roof system that does not meet the design intent of the system and is not easily repaired and requires major rework. Also all components of the system should have the same long-term life cycle. Also a lack of a maintenance plan from day 1 is a failure.
18. I define green roof failure as either the roof leaking thus not protecting what it was intended for or failure of it to provide the aesthetic effect it was intended for.
19. A circumstance in which one or more of the design goals is not met. Such goals are project specific, and may include: roof functionality, stormwater retention, habitat creation, aesthetics, insulating ability, urban heat island amelioration, among others.
20. Build-up of water in one section of roof resulting in leakage. Water line reached above waterproofing level and sealant at this area had dried and cracked.
21. Lack of thriving plants, presence of invasive weed species.
22. A roof failing to perform as specified in the system design.
23. A green roof failure can be defined as a vegetated roof which has difficulty establishing plant material or when the assembly does not drain storm or irrigation water effectively (in the designed time).
24. A green roof fails when it no longer provides the benefits that it was designed for. Coming from a nursery, plant grower background, I would like to say a green roof fails if it is no longer green (living plant material.) However a green roof designed solely for storm water management may continue to accomplish this goal without live plant material if the media remains intact. Of course it is debatable if the media would remain intact and if that would really qualify as a green roof anyway. So perhaps a green roof does need to remain green but even a living green roof can fail if it no longer provides the functions it was designed for such as aesthetics, heat island cooling, stormwater management, etc. My answers to some of the items below should be evaluated in this light. They are only failures or potential failures if the green roof was originally designed to accomplish those aspects. For example, a healing garden at a medical facility can be designed solely for aesthetics in which case it would not be a failure if it retained less than 30% of the average rainfall.
25. Failure is when the plants die.

26. Failure occurs when the system cannot support plant life sufficiently and plant coverage decreases year after year, and cannot be corrected by mere plant replacement.
27. Any significant failure in aesthetics, function or operation of the system that doesn't meet the original intent of the agreed upon design, function, and performance objectives.
28. This would depend on the function that the green roof was designed to serve. Is the green roof providing stormwater management, habitat, heat island benefits, prolonging the life of the roof?
29. A green roof failure occurs when intended function of the green roof is no longer recognized.
30. On a green roof it is all about the plants and compromising the health of the plants is failure.
31. Like the industry as a whole there is a lot of variation. Failure could be dead plants, but overall it should be defined by the projects inability to deliver the design intentions.
32. Green roof failure is defined by negative trends in vegetation health, effluent water quality, and/or rainwater absorption resulting in excessive maintenance.
33. A green roof failure is reached when the roof provides no net benefit to the building or surrounding environment, and in order to correct the issue(s), a completely new system must be installed.
34. A significant part or combination of the parts that make up the green roof system no longer functioning as intended. The degree or question of failure depends heavily on the original design brief for the green roof.

Question 2: Numerated Definition Responses Provided by GR Experts

Approaching the definition of GR failure from a numerical perspective, Q2 asks respondents to associate a list of issues to the potential for GR failure. This closed-end question was offered after posing the same question in an open-ended format to avoid leading respondents toward specific answers as per Hay (2010). Results for Q2 are tabulated in Table 30, below.

Survey Question 2: "From the following list of issues often associated with green roof *design, installation, and maintenance*, please click on one box per row to indicate the role each item contributes to green roof failure. Would you say the issue is 'not an aspect of failure;' 'a potential failure if left untreated;' OR 'an actual failure'?"

Table **30**.

Percentage and "n" Values of Expert Respondents Answering Question 2 (closed end format)

Association of Issue w/ GR Failure → **↓ Potential GR Issues Chosen by Survey Participant** (sorted by highest % of respondents)	**Not an Aspect of GR Failure**	**A Potential Failure if Left Untreated**	**An Actual Failure**	**Total Count (n =)**
• Plants "wander" from original planting location(s)	**95.35%** 41	4.65% 2	0.00% 0	43
• The appearance of plantings in dormancy or "off-season(s)" is unacceptable	**88.37**% 38	11.63% 5	0.00% 0	43
• Green roof leakage has permanently damaged the substructure	9.52% 4	4.76% 2	**85.71**% 36	42
• Green roof installation is too heavy for the substructure	9.09% 4	9.09% 4	**81.82**% 36	**44**
• Green roof harbors pests that damage protective roof liner	4.76% 2	**73.81**% 31	21.43% 9	42
• Green roof harbors weeds that damage roof liner	0.00% 0	**72.09**% 31	27.91% 12	43
• The green roof leaks more than a conventional roof	9.52% 4	21.43% 9	**69.05**% 29	42
• Poor/no substrate drainage (substrate is below drainage outlet, plants drown)	4.55% 2	29.55% 13	**65.91**% 29	**44**
• Green roof requires specialized maintenance staff to manage weeds	**58.14**% 25	34.88% 15	6.98% 3	43
• Green roof plantings require irrigation to supplement precipitation	**58.14**% 25	30.23% 13	11.63% 5	43
• Green roof requires specialized maintenance staff to manage irrigation system(s)	**55.81**% 24	25.58% 11	18.60% 8	43
• Potentially required nutrients negatively affect stormwater quality	18.60% 8	**53.49**% 23	27.91% 12	43
• More than 25% of the plants require annual replacement (non-food green roofs only)	16.28% 7	**51.16**% 22	32.56% 14	43
• Soil substrates clog storm drainage system(s)	0.00% 0	**50.00%** 22	**50.00%** 22	**44**
• Soil substrates have eroded too rapidly	2.27% 1	**50.00**% 22	47.73% 21	**44**
• Green roof leaks are impossible to locate/fix w/o removing installation	34.88% 10	**46.51**% 9	18.60% 23	42

Question 2 Respondent Comments

Survey Question: "From the following list of issues often associated with green roof *design, installation, and maintenance*, please click on one box per row to indicate the role each item contributes to green roof failure. Would you say the issue is 'not an aspect of failure;' 'a potential failure if left untreated;' OR an actual failure'?"

1. Regarding the above, a green roof that leaks is a membrane issue, not a green [roof] issue.
2. Sorry to write this here but: there are also flooded roofs (retaining roofs) that are designed to do that so it must not be a failure that they flood (staunch roof? German: Anstaudach). I personally see roofs that just inhabit under 5 species a complete ecological failure.
3. Product or workmanship related?
4. Design intent changes with climate, functionality focus of the installation and long-term considerations such as matching design intent with a client's expectation, for example: Flooded green-roof substrate may be a successful/functional outcome if designing for aquatic habitat and requiring specialist staff to fulfill general maintenance outcomes may be a successful outcome, pending client expectations. Each site should be designed with site-specific considerations in mind. Rolling out a uniform approach to all designs/products/outcomes does not cater for change, culture, climate and specialization advancement. Reaching a successful outcome should still be achieved via a scientific approach, utilizing all available data to develop a robust outcome to cater for diversity, over monotypic or super-efficient mediocrity.
5. The early questions in this section are subject to the design intent and the evolving view of the green roof by the client.
6. I am not sure I totally understand how to answer this question.
7. The green roof doesn't leak, the roof/waterproofing does. Unless the leaks can be traced directly to damage or other issues during installation of the green roof, leaks should not be considered a failure of the green roof, but of the entire system.
8. There's a ton of other failures I've seen. Contractors have installed the root barrier above the drainage mat, or the wrong growing media is used either in design or installed. A good design doesn't require fertilizers applied after being installed.
9. Really, several of the questions are more nuanced than the answer choices allow.
10. Definition of acceptable, weeds, and specialized maintenance is required to answer the questions correctly.
11. In short, the questions involving the green roof leaking are subject to question... greenroofs are supposed to drain (leak) the issue is from the poor choice of waterproofing.

Survey Respondent Data Question 3

Survey Question 3: "From the following list of issues often associated with green roof economics and the environment, please click on one box per row to indicate the role each item contributes to green roof failure. Would you say the issue is 'not an aspect of failure;' 'a potential failure if left unaddressed;' OR 'an actual failure'? " Answers in Table 31, below, are sorted by the issue's "actual" association with GR failure.

Table 31.
Percentage and "n" Values of Respondents Answering Question 3

Association of Issue w/ GR Failure → **Potential GR Issues Chosen by Survey Participants ↓** (sorted by highest Actual Failure)	**Not an Aspect of Failure**	**A Potential Failure if Left Untreated**	**An Actual Failure**	**Total Count (n =)**
• Green roof fails to sustain plant growth	4.76% 2	21.43% 9	**73.81%** 31	42
• Green roof negatively effects property value	38.10% 16	26.19% 11	**35.71%** 15	42
• Green roof fails to sufficiently exceed the lifespan of a conventional roof	34.15% 14	29.27% 12	**36.59%** 15	41
• Green roof impedes resale of property	48.84% 21	30.23% 13	**20.93%** 9	43
• Green roof fails to moderate structure's internal temperature	57.14% 24	26.19% 11	**16.67%** 7	42
• Green roof reduces access to mortgage financing	46.51% 20	39.53% 17	**13.95%** 6	43
• Green roof fails to buffer external noises	58.54% 24	29.27% 12	**12.20%** 5	41
• Green roof ROI fails to meet target	51.16% 22	37.21% 16	**11.63%** 5	43
• Green roof increases insurance rates and/or limits insurance availability	48.84% 21	39.53% 17	11.63% 5	43
• Green roof fails to attract beneficial insects and/or wildlife	41.46% 17	48.78% 20	9.76% 4	41
• Green roof doesn't offer cooling benefits to building's neighboring climate	60.98% 25	29.27% 12	9.76% 4	41
• Green roof fails to filter air and/or water pollutants before draining	46.34% 19	46.34% 19	7.32% 3	41
• Green roof doesn't offer aesthetic benefits to building occupants	53.66% 22	39.02% 16	7.32% 3	41
• Green roof installation costs more than initially budgeted	55.81% 24	39.53% 17	4.65% 2	43

Question 3 Respondent Comments

Survey Question 3: "From the following list of issues often associated with green roof economics and the environment, please click on one box per row to indicate the role each item contributes to green roof failure. Would you say the issue is 'not an aspect of failure;' 'a potential failure if left unaddressed'; OR 'an actual failure'?"

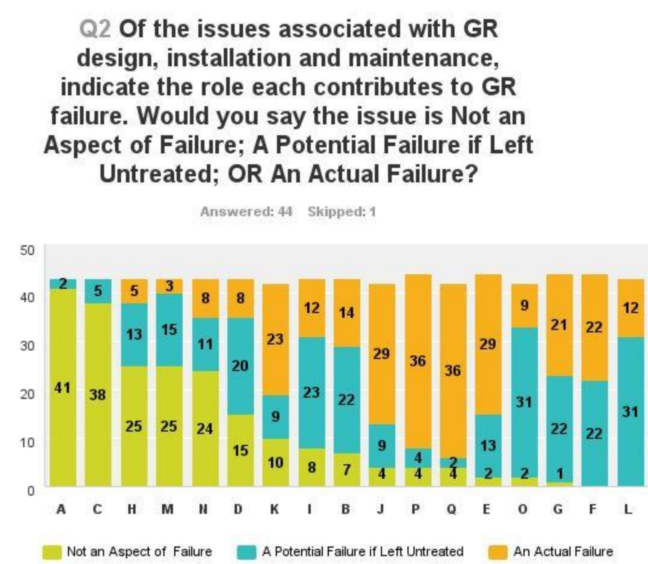
1. On their own, I don't see these as an aspect of failure. Together or a number of them combined I would see as an aspect of failure.
2. The goals and costs of every green roof are different. The costs/benefits need to be addressed on a site-by-site basis. A green roof that doesn't offer some particular benefit doesn't make it a failure.
3. In these cases, the green roof may not function as intended, but actual failure of the green roof would be limited to waterproofing, structural, or plant failure.
4. Matching design intent to client/functionality expectation is a primary focal point. Producing a "folly" can still be a successful if it fulfills the client's primary requirements. A single green-roof technology cannot be expected to fulfill every conceivable functionality simultaneously. Adapting design and installation to focus on maximizing specific functionalities, requires amendment to various components comprising green roofs, e.g., maximizing thermal vs. acoustic insulation require individual component alteration, including adapting the plant palette to best address each outcome. No single installation type will address every functionality simultaneously. Each functional tangent presents trade-offs requiring to be accurately and effectively presented to the client and balanced to achieve a suitably tailored response to achieve the client's expectation. This often requires client education addressing each separate area of specialization.
5. So many of these are subject to outside forces such as real estate values or people's definition of what is beautiful. I can't assign failure. Some of the others are just sales promises and not realistic design goals
6. What was the roof intended to do? what were the issues it was to address? Was it designed to buffer sound, etc.?
7. All of these items are failures but only IF the green roof was designed for those specific elements. Budgeting is frequently done by unqualified personnel, in which case the failure is not a green roof failure.
8. Answers to all of these questions depend on the goals of the specific installation.
9. This question is a bit confusing in that the failure depends on the intended use of the green roof.
10. All additional benefits other than stormwater retention and increasing lifespan of roofing are not relevant if the plants are thriven and healthy. The problem is in the green roof design/construction where too many people rely on roofing manufacturers and their warranties.
11. I checked all the middle boxes because I don't know what the design intent was for this particular green roof?? Was the goal of the roof to reduce the cooling loads? Retain stormwater, etc. Analysis of Answers to Survey #1

Expert Definitions in Response to Survey #1, Question #2

Q2. "From [a] list of [17] issues often associated with GR design, installation and maintenance, please click on one box per row to indicate the role each item contributes to green roof failure. Would you say the issue is 'not an aspect of failure;' 'a potential failure if left untreated;' OR, 'an actual failure'?"

As indicated in the question above, types and rates of failure associated with GR issues associated with design, installation, and maintenance were outlined by 41 GR industry experts. Association of failure with specific issues is similar to responses provided in Q1, which sought generalized definitions of failure from respondents. The priority of results provided by respondents to Q2 (see Appendix C for verbatim list), however, is different. Plant survival stands out more often as a point of non-failure, while the need for specialized staff to manage weeds and irrigation is more frequently associated with potential GR failure. Less distinct in terms of respondent agreement, but more distinct in terms of association with actual failure, are leakage-related issues.

A graphic summary of the findings follows in Figure 21, below.



<u>KEY to Q2 Failure Issues Occurring in Green Roofs</u>

A. Plants "wander" from original planting location(s)
B. >25% of plants require annual replacement (non-food GRs)
C. Appearance of dormant/off-season plantings unacceptable
D. Planting media fails to retain 30%+ of average rainfall
E. Poor/no media drainage (media below outlet, plants drown)
F. Soil media clog storm drainage system(s)
G. Soil media has eroded too rapidly
H. GR plantings require supplemental irrigation
I. Potentially required nutrients (-) impact stormwater quality
J. The GR leaks more than a conventional roof
K. GR leaks impossible to locate/fix w/o removing installation
L. GR harbors weeds that damage roof membrane
M. GR requires specialized maintenance staff to manage weeds
N. GR requires specialized maintenance staff to manage irrig. system(s)
O. GR harbors pests that damage protective roof membrane
P. GR installation is too heavy for the substructure
Q. GR leakage has permanently damaged the substructure

Figure 21. Summary of Q2 from Survey #1.

Similar to survey Q1, solicited comments to Q2 effectively noted that certain GR features "…are subject to the design intent and the evolving view of the green roof by the client**"** (response #26); "Design intent changes with climate, functionality focus of the installation and long-term considerations such as matching design intent with a client's expectation, for example: Flooded green roof substrate may be a successful/functional outcome if designing for aquatic habitat and requiring specialist staff to fulfill general maintenance outcomes may be a successful outcome, pending client expectations. *Each site should be designed with site-specific considerations in mind. Reaching a successful outcome should still be achieved via a scientific approach, utilizing all available data to develop a robust outcome* to accommodate diversity, over monotypic or super-efficient mediocrity" (response #30; emphasis added).

This latter comment highlights the balancing act that designers of GR are challenged to achieve. In several respects, GR projects can be limited by cost constraints and/or unchangeable site aspects. Unless the client can be responsibly convinced of or educated about the realities of GR costs and benefits, the need to fulfill client expectations remains the objective industry members may or may not be compelled to achieve, even if the outcome results in an increase in long-term GR failure.

As noted earlier in this analysis section, there were multiple distinctions made between the GR and the roofing membrane or waterproofing barrier (both are seen as an element separate from the GR):

> "…green roofs are supposed to drain (leak); the issue is from the poor choice of waterproofing" [response **#4**]; "…a green roof that leaks is a membrane issue, not a green issue" [**#40**]; and "The green roof doesn't leak, the roof/waterproofing does. Unless the leaks can be traced directly to damage or other issues during installation of the green roof, leaks should not be considered a failure of the green roof, but of the entire system" [response **#23**].

Another comment addressed the appropriate installation of waterproof barriers:

> “There's a ton of other failures I've seen. Contractors have installed the root barrier above the drainage mat, or the wrong growing media is used either in design or installed….” [response **#22**].

A comment regarding leaks follow:

> “One of the ‘biggest failures’ I can remember is the leaks on the California Academy of Science. Great GR, really pushed the technology into the lime light, however there were a lot of experimental elements to it as well such as the waterproofing around the skylights, the [coconut coir] baskets with pre-grown plants on steep domes, etc. When the public asks CAS staff if the roof leaks they just say, ‘yes’ without telling them that most GR don't leak, but this one had leaks that are now resolved. So many visitors have this false impression of the risk of leaks. When they look at the steep slopes of the domes and see erosion, the public doesn't know about insufficient maintenance, they just leave thinking that GR can only be used on flat roofs. Projects that spread misconceptions of the technology are huge setbacks to the technology as well as other types of green infrastructure” (personal communication, R. Garcia, ASLA, Infrastructure Division, San Francisco PUC, February 23, 2016).

Questions, comments, complaints, and rebuttals were also posed by several of the survey respondents, including the following comments:

- ❑ "So many of these [issues] are subject to outside forces such as real estate values or people's definition of what is beautiful. I can't assign failure. Some of the others are just sales promises and not realistic design goals."
- ❑ "Definition of acceptable, weeds, and specialized maintenance is required to answer the questions correctly."
- ❑ “I have yet to work on a problem free project, and personally I think it's critical for the industry to be aware of challenges so that the field can progress. We learn more from failures than successes. If there aren't failures, then the field isn't pushing boundaries. A certain amount of failures is critical, but it's important to manage the awareness so the perception is proportional.”
- ❑ “A great challenge with any green roof system is that most times the ‘product’ or system design is blamed for the challenges when instead it is a result of poor workmanship, and other times it is poor system design (either waterproofing and/or green roof component compatibility) and not poor workmanship. Also, the definition of failure may differ depending on the market region and segmentation.”

- ❑ "There are several issues here (e.g. loading and waterproofing) that are not related to green roof failure and these should not be included" (personal communication, N. Baumann, February 23, 2016).

❑ "Surveys are problematic as they may be asking the wrong questions that can bias the survey. I think the vast majority of the questions are loaded against green roofs. Most of the questions, to be honest, deal with waterproofing issues. To follow this my thoughts while filling out the survey.

"The question is whether leak is due to bad installation of waterproofing or as a consequence of the green roof element. 99% of time the green roof element is blamed but it is the waterproofing layer or installation that is actually at fault.

"**Green roof harbors weeds that affect the liner**—again this is not a green roof failure as such—it is lack of root barrier—which these days is incorporated into the waterproofing 95% of the time. Therefore bad choice of waterproofing and/or bad installation of waterproofing. To be honest the weed issue affecting the waterproofing is a bit of a myth—used to happen a lot in late '70s and early '80s in Germany but I have never heard of or witness this kind of failure in all my time involved in green roofs. 98% of failure in terms of leaks are due to waterproofing issues not the green roof element. I am sure Wolfgang and Jorg will tell you otherwise!!!! ;)

"**Pests affecting protection layer**! Well this is a new one for me—must be careful we don't invent issues. I am sure people say yes this is a failure. Two examples—wood mice investing in insulation at Eden Project—I wouldn't call this a failure—I would call it an issue (roof is connected to wider countryside. Mites causing bites on children in Cumbria (Google)—blamed on the green roof. Later discovered that mites came from the golf course not the green roof. However green roof was deemed a failure even though ever learned entomologist in UK said there was no way the green roof was to blame—SCAREMONGERING.

"**Green roof installation is too heavy for the substructure**—this is 99% not a green roof failure but a serious engineer's failure to load roof correctly pre-design. I do know of one very tragic and sad instance in Latvia—https://en.wikipedia.org/wiki/Zolit%C5%ABde_shopping_centre_roof_collapse — sadly as president of EFB I had to write a difficult letter to Latvian government expressing our condolences and explaining from our Federation what probably happened. This was bad installation process not that green roofs are failures. The metric tonne substrate bags were left on the roof unspread overnight. This should not happen if our codes of practice are followed (FLL

> GRO and the rest of Europe). Sadly, a severe overnight storm compounded the problem and many died.
> Regarding questions due to **benefits not acquired**—god knows how anyone is going to prove this, therefore I have to leave blank...” (personal communication, Dusty Gedge, February 23, 2016).

The latter portion of the above responses highlights that issues occur at multiple points along the path to GR installation, not to mention those occurring after the GR is free and clear of warranties.

The respondent suggesting that “several of the questions are more nuanced than the answer choices allow” [response **#11**] is worth noting. This issue suggests a need for future surveys that ask experts to clarify the critical aspect of roof and membrane leaks as a component, rather than a separate element of GR function. Another respondent accurately noted that the survey fails to query product or workmanship as a potential element of GR failure.

Design, Installation, and Maintenance Issues Related to Green Roof Failure

A summary perspective of the failure categories associated with GR design, installation, and maintenance (separate from economic and environmental considerations) and the order of respondent selections in each, follows. See Table 32 for a matrix that summarizes these results.

Analysis of Issues Potentially Correlating to Green Roof Failure

Issues Associated with Green Roof Failure:

Issues that a majority of survey respondents deem to be “an actual GR failure” follow. It is worth repeating that what may be most important to consider is that (untreated) failure issues tend to snowball, or lead to and/or otherwise amplify other issues. The responses with the highest selection counts are listed first and then in declining order of respondent selection. Emphasis has been added to issue titles to highlight important issue differences.

Ranking of All Issues Cited by GR Owners and Managers

Table 32.
Experts' Selection of Issues that Associate with Green Roof Failure (All Issues, Ranked by % of Highest Response)

Rank of Issue	Qs 2. +3. Defining Issues that Might (Not) Associate w/ GR Failure (survey respondents chose between three values: Not, Potentially, or Is Associated w/ Green Roof Failure)	NOT associated w/ Failure	Potentially associated w/ Failure	IS associated w/ Failure	Survey Participation (n=)	% of respondents in Highest category
1	GR installation is too heavy for the substructure	3	2	30	35	85.7%
2	GR leakage has permanently damaged the substructure	3	2	28	35	80.0%
3	The green roof leaks more than a conventional roof	3	3	27	34	79.4%
4	GR fails to sustain plant growth	1	6	26	33	78.8%
5	Poor/no substrate drainage (substrate is below drainage outlet, plants drown)	2	8	25	35	71.4%
6	GR leaks are impossible to locate/fix w/o removing installation	9	5	19	34	55.9%
7	Soil substrates have eroded too rapidly	1	15	19	35	54.3%
8	Soil substrates clog storm drainage system(s)	0	16	19	35	54.3%
9	>25% of plants require annual replacement	3	18	13	34	52.9%
10	GR fails to sufficiently exceed the lifespan of a conventional roof	9	11	12	32	37.5%
11	GR has a negative effect on property value	14	8	11	33	42.4%
12	Nutrients negatively affect stormwater quality	6	17	11	34	50.0%
13	GR harbors weeds that damage roof liner	0	25	9	35	71.4%
14	GR requires specialized maintenance staff to manage irrigation system(s)	17	9	8	34	50.0%
15	GR harbors pests that damage protective roof liner	1	24	8	34	70.6%
16	GR impedes resale of property	18	9	7	34	52.9%
17	Planting substrate fails to retain 30% or more of average rainfall	11	16	7	34	47.1%
18	GR fails to moderate structure's internal temperature	17	10	6	33	51.5%
19	GR fails to buffer external noises	17	10	5	32	53.1%
20	GR plantings require irrigation to supplement precipitation	19	10	5	34	55.9%
21	GR increases insurance rates and/or limits insurance availability	18	11	5	34	52.9%
22	GR reduces access to mortgage financing	18	11	5	34	52.9%
23	GR doesn't offer cooling benefits to building's neighboring climate	19	10	3	32	59.4%
24	GR doesn't offer aesthetic benefits to building occupants	16	13	3	32	50.0%
25	GR requires specialized maintenance staff to manage weeds	18	13	3	34	52.9%
26	GR return on investment fails to meet target	17	14	3	34	50.0%
27	GR fails to filter air and/or water pollutants before draining	13	16	3	32	40.6%
28	GR fails to attract beneficial insects and/or wildlife	12	17	3	32	37.5%
29	GR installation costs more than initially budgeted	20	14	1	35	57.1%
30	Plants "wander" from original planting location(s)	34	0	0	34	100.0%
31	Appearance of plantings in dormancy or "off-season(s)" is unacceptable	30	4	0	34	88.2%
Rank of Issue	Qs 2. +3. Defining Issues that Might (Not) Associate w/ GR Failure (survey respondents chose between three values: Not, Potentially, or Is Associated w/ Green Roof Failure)	NOT associated w/ Failure	Potentially associated w/ Failure	IS associated w/ Failure	Survey Participation (n=)	% of respondents in Highest category

Issues Associated with Green Roof Failure (cont):

- ❑ **Green roof installation is too heavy for the substructure**: Not surprising was the agreement among 85% of the survey respondents (34 people) regarding potential structural failure that might result from miscalculating GR dead and live loads. Two respondents (~5%) indicated that too much weight was only a potential failure; four other respondents indicated that it was not a failure at all (10%; 4 people).

- ❑ **Green roof *leakage* has permanently damaged the substructure**: Also unsurprising was the number of respondents correlating GR failure associated with leakage (~84%; 31 respondents). Two respondents (~5%) perceived leakage to be a "potential GR failure if left untreated," and four more (~10%) did not associate leakage issue with GR failure.

- ❑ **Poor/no substrate drainage (substrate is below drainage outlet, *plants drown*)**: Nearly 70% (27 respondents) perceive poor/no substrate drainage as an "actual" failure; while more than 25% (10 respondents) perceive drainage issues to be only a potential failure. Two individuals (~5%) suggested that drainage issues were not a failure.

- ❑ **The green roof leaks *more* than a *conventional* roof**: More distinct than poor drainage as an issue was the delineation by respondents regarding the rate of GR leaks compared to conventional roofing. Here, slightly more than 70% of respondents (21 people) perceive a greater relative potential for GR leaks to associate with failure, while ~18.4% (7 people) perceive it to be a potential GR failure.

- ❑ **Soil substrates clog storm drainage system(s)**: Nearly 54% (21) of the respondents perceive that planting media clogs represent an actual GR failure, while more than 46% (18 respondents) perceive that clogs represent only a potential failure. There were no votes cast in the "Not a GR failure" category, which signifies complete agreement.

- **Green roof leaks are impossible to *locate/fix* w/o removing installation**: Here, nearly 26.3% (10 respondents) do not perceive the difficulty of repairing GR leaks as a failure; ~18.5% (7 people) perceive it to be a potential GR failure, while ~55.3% perceive difficulties with leak repairs to be an actual GR failure.

- **Soil substrates have eroded too rapidly**: As noted earlier, respondent perception of this issue was evenly divided between "Potential" and "Actual" failure (~47%; 19 respondents each). One respondent suggested that it was not a failure issue. This amount of divergence on an issue that is difficult to repair could be an indicator that the survey asks too much from too broad a range of experts. It also starts to confirm the author's suspicion that survey fatigue had set in.

Issues Associated with Potential Green Roof Failure if Left Untreated:

Issues that a majority of survey respondents deem to be "potential failures if left untreated" follow. What may be most important for the reader of this thesis to consider (especially if he or she is a potential GR consumer) is that untreated issues tend to snowball, or lead to and/or otherwise amplify one another. Once again, the responses with the highest selection counts are listed first and the remainder in declining order of respondent selection. Emphasis was also added to issue titles to highlight important issue differences.

- **Green roof harbors *pests* that damage roof liner**: Slightly more than 71% of survey respondents (27 people) agree with the association between pests and potential GR failure. Only two respondents (5%) didn't associate pests with GR failure, leaving nine others (24%) who perceive that pests do associate with GR failure. Throughout the author's GR failure literature research, little was found that addressed pests affecting GR membranes (as well as irrigation system pipes). Then again, the author wasn't looking specifically for this topic.

- **Green roof harbors *weeds* that damage protective roof liner**: Similar to the potential for pest damage, just over 70% (27 respondents) think that weeds associate with GR failure. More important is that an additional 30.8% of respondents (12 people) do perceive weeds as a GR failure issue. This set of statistics provides strong evidence that aesthetics count, even to members of the GR industry. Where agency and, to a lesser degree, industry interests overlook this detail is where they start to lose a significant share of potential GR consumers. Problematic to the issue, however, is the often-unknown correlation between weed growth and irrigation (the more one waters, the more the weeds grow).

- ❑ **Potentially required *nutrients* negatively affect *stormwater* quality**: The range of responses to this issue is sobering to this author: a full 50%, or 19 respondents, perceive the leaching of GR fertilizers and weed or pest-related chemical controls as "a potential GR failure;" ~29%, or 11 respondents, perceive the same leachates to be "an actual failure;" with the remaining 21%, or 8 respondents, perceiving these GR chemical leachates to be "not an aspect of GR failure."

  The same problems that associate weed growth with irrigation similarly associate negative impacts upon stormwater quality with the application of nutrients—especially on irrigated GRs. This is especially true of quick-release fertilizers, which cannot be relied upon to either enhance communities of beneficial soil critters desired in GR soil media or replenish organic matter washed out of GR soil media profiles by irrigation systems and by rainfall. To a sustainably oriented horticulturalist, it seems just as important to not only slow the rate of stormwater (a key objective of many municipalities that promote GRs), but to also filter or otherwise keep water that moves through GR profiles clean before being allowed to enter area water bodies. Promotion of GRs does not have to forgo water quality concerns, but may benefit from the incorporation of awareness-building that addresses these issues in training offered to potential GR consumers and expected of certified GR professionals.

- ❑ **Soil substrates have eroded too rapidly**: Respondent selection of this issue was evenly divided between "Potential" and "Actual" failure (~47%; 19 respondents selecting each). One respondent suggested that the rapid loss of GR soil substrates was not a failure issue. This type of outlier is hopefully representative of a person who preferred to complete the survey more quickly than to answer it thoughtfully.

- ❑ **More than 25% of the *plants* require annual *replacement* (non-food green roofs only)**: The bulk of the responses (~45%; 17 respondents) see this rate of plant loss as a potential failure, while the next largest count ~37% (14 respondents) perceive that this rate of plant loss does indeed constitute a failure. A few respondents (~18%; 7 total) appear to expect plant mortality and are not concerned with this rate of annual loss.

- ❑ **Planting substrate fails to *retain 30%* or more of average *rainfall***: More than 41% of respondents (16 survey participants) associate the lack of stormwater retention as a potential GR failure. Another 38.5% (15 respondents) do not associate the lack of stormwater retention with GR failure. The remaining 20.5% of respondents (8 people) do associate the lack of stormwater retention with GR failure.

Oddly, associating these responses with the type of industry represented by the respondent reveals that most people serving public agencies whose primary objective is stormwater management answered this question as a non-issue(!). Of the individuals perceiving that GR plant media should retain at least 30% or more of average rainfall, most are European, or are first-hand GR customers. Perhaps this distinct disconnect indicates either oblique wording of the issue on the author's part and/or survey respondent fatigue.

Issues Not Associated with Green Roof Failure:

Issues that most survey respondents deem are "not an aspect of failures" follow. Once again, what may be most important for the reader of this thesis to consider (especially if he or she is a potential GR consumer) is that untreated issues tend to snowball, or lead to and/or otherwise amplify other failures. This section also reflects quite clearly the current disinterest by agencies and the GR trade in the interests of the GR consumer. Once again, the responses with the highest selection counts are listed first and then in declining order of respondent selection. Emphasis has been added to issue titles and corresponding highest values to highlight important issue differences.

- **Plants "wander" from original planting location(s)**: Even if the customer is unprepared for this likely potential, nearly 100% of respondents (36 total) agree that plants growing beyond their original placement does not constitute a failure. Therein may be a key to one of the issues in marketing future GRs. None of the respondents found this issue affiliated with failure, but the remaining 5.26% of the respondents (two people) felt that it could become problematic enough to create failure if left untreated.
- **The *appearance of plantings* in dormancy or "off-season(s)" is unacceptable**: Similar to the expectation that GR plants will wander is the expected change in GR aesthetics that GR customers tend to dislike. A smaller "Not an Aspect of Failure" vote was cast here, however, (~87%; 33 total), while five votes (12.8 %) were cast in the direction of potential failure. This appears to indicate that industry members are fully aware that green roofs lose visual appeal in certain seasons. Yet customers sometimes have a desire, if not an expectation, that their GRs will provide aesthetics throughout all seasons, not just when plants are performing their best. One comment noted that a "definition of acceptable… is required to answer the question correctly" [response **#6**].

- **Green roof *plantings require irrigation* to supplement precipitation**: Like the range of responses relating to the need for specialized staff for weed management (below), 56.4% of survey respondents (22 total) do not associate the requirement of irrigation with GR failure. Nearly 31% of respondents (12 total), however, rated their perception of required supplemental irrigation as "a potential failure if left untreated." The remaining five respondents (12.8 %) do associate GR failure with the requirement of supplemental irrigation. This is due, in part, to the fact that only one missed irrigation cycle on an unusually hot day, with or without an extended dry spell, can severely stress or permanently kill even the tough plants used in GR installations.

  The thesis author predicts that respondents answering with the majority in this question will be tested in the future, when water supplies are limited enough that GR irrigation becomes a costly and sometimes banned luxury. This issue starts to delineate the different expectations of GR performance among different GR affiliates. For example, municipal utility and public agency representatives who have an interest in the storm drainage benefits that GRs can provide are among a majority of the respondents who are also not worried about GR aesthetics (typically a result of supplemental irrigation). GR owners desiring aesthetic installations and energy providers who see GR installations as a means of moderating summer building temperatures (both inside and out) may be left in the sun when water becomes scarce. This prediction will be realized when climate change brings extended spells of increasingly hotter and longer dry spells to the region, as it did during the summer of 2015.

- **Green roof requires *specialized maintenance* staff to manage *weeds***: With nearly the same range of responses as the option regarding GR irrigation (above), 56.4% of survey respondents (22 total) indicated an understanding that weeds will not only happen to a GR (especially a newly installed GR) if left unmanaged, but that weed management requires specialized skills. While this majority does not see an association with the need for specialized maintenance skills as an aspect of GR failure, GR owners might see it as an unanticipated and/or increased long-term cost burden. A higher count of respondents (12 total; ~36%) further defines the need for specialized maintenance as a potential failure if left unmanaged.

  Whether or not GR owners understand GR maintenance requirements and are either ready to pay for the service of a knowledgeable maintenance contractor, know enough to do so themselves, and/or are willing to commit to the long-term maintenance demand that a GR requires is another matter worthy of added research. One respondent suggested that the "definition of …weeds … is required to answer the question correctly" [response **#6**]. The author would add that a better definition of "specialized maintenance" would help to clarify the type of knowledge that the desired GR maintenance contractors may be expected to have. There is little worse than spending money on plants only to have a maintenance person pull, poison, or otherwise destroy them because they don't know (or know how to handle) the plants with which they are working. This is a difficult industry issue because of the high rate of employee turnover, the low degree of education, and the higher rate of language and/or cultural barriers associated with the immigrant populations who tend to occupy a bulk of the GR maintenance community. This issue, in particular, also has bearing upon the landscape and green infrastructure industries at large, and the author believes the negative impacts it creates are underestimated in terms of water quality and solid waste issues. This issue is discussed further in the thesis summary.

- ❑ **Green roof requires *specialized maintenance* staff to manage *irrigation* system(s)**: Last among the issues with a majority of respondents selecting "Not An Aspect of Failure" is the point identifying irrigation as a potential requirement. Here, nearly 54% of respondents (21 people) indicated no affiliation between the need for specialized staff for irrigation system management and the fallout that can occur with poorly managed irrigation systems. Higher, however, is the number of respondents who perceive that the failure of GRs is associated this issue (20.5%; 8 respondents).

  These response rates appear to echo the prior responses associated with potential requirement of supplemental irrigation, while the different percentages relating to whether or not specialized maintenance staff is an aspect of failure if left untreated acknowledges the issue and/or has experienced GR failures related to mismanaged irrigation systems. One respondent suggested that a "definition of … specialized maintenance is required to answer the question correctly" [response **#6**].

  The 12 remaining issues showing responses that were "not an aspect of failure".

Expert Definitions in response to Survey #1, Question #3

Q3: "From [a] list of [14] issues often associated with GR economics and the environment,
please click on one box per row to indicate the role each item contributes to green roof failure. Would you say the issue is 'not an aspect of failure;' 'a potential failure if left untreated;' OR, 'an actual failure'?"

Economic and environmental categories of issues related to GRs are respectively associated with return on investments made by consumers and with functional intentions, typically identified by GR planners and as objectives of GR consumers. This section's scores may reveal survey fatigue, but they are nevertheless sobering. The values chosen sometimes defy market logic, which would suggest that people pursue the best return on their investments. At the same time, the scores show how environmentally oriented objectives compare with other more severe failure issues. Accommodation of these interests can represent areas of potential failure improvements worthy of consideration by public agencies and the GR industry alike. As with prior questions in this survey, the resulting responses were divided into the three failure categories, below, and sorted in declining order of respondent selection.

A graphic summary of Q3 results is provided in Figure 22, below.

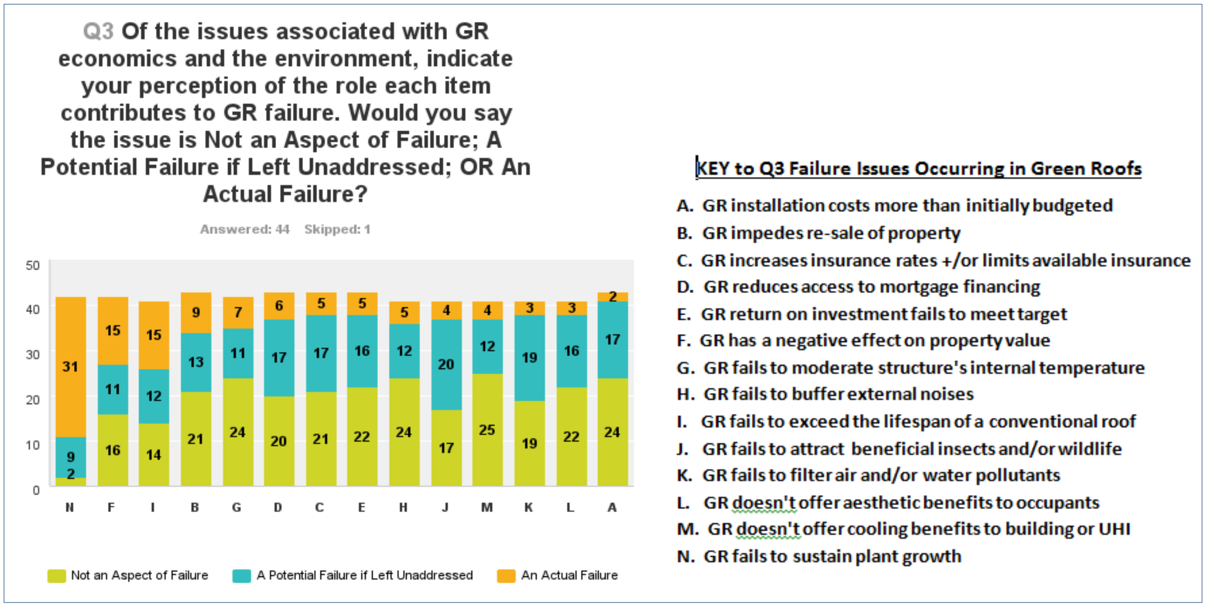


Figure 22. Summary of Q3 from Survey #1

Analysis of Economic and Environmental Issues Associated with GR Failure

Of all issues evaluated, failure of GR plantings and an inability to extend the membrane lifespan rank as the third and fourth highest failure associations. These same issues show up in the results of the second survey as well. Next noted by experts as key influences on GR failure are maintenance-related issues, particularly plant dieback. Using the responses from GR experts, the following categories were created to further rank issues among the GRs in Portland, Oregon.

Issues Associated with Green Roof Failure:

- **Green roof fails to sustain plant growth**: Nearly 74% of respondents (28 people) associate GR failure with the loss of GR plants. Slightly more than 21% (8 respondents) see plant failure as a potential issue that associates with overall GR failure and two individuals do not see any problems associated with plant loss (5.26%).

- **Green roof fails to sufficiently exceed the lifespan of a conventional roof:** Scores correlating the lifespan of a structure's roof because of GR-related issues were rather evenly spread with 13 respondents (35.14%) perceiving this issue to be an actual failure and 13 (35.14%) perceiving it to not be an actual failure. The remaining 29.73% of survey respondents (11 total) perceive that the failure to meet or exceed the lifespan of a conventional roof as a potential failure.

Issues Associated with Potential Green Roof Failure if Left Untreated:

- Green roof fails to attract beneficial insects and/or wildlife (43.24%, 16 Not; 45.95%, 17 Potentially; 10.81%, 4 Does)

Issues Not Associated with Green Roof Failure:

- Green roof doesn't offer cooling benefits to building's neighboring climate (62.16%, 23 Not; 27.03%, 10 Potentially; 10.81%, 4 Does)

- Green roof fails to moderate structure's internal temperature (57.89%, 22 Not; 23.68%, 9 Potentially; 18.42%, 7 Does)

- Green roof fails to buffer external noises (56.76%, 21 Not; 27.73%, 11 Potentially; 13.51%, 5 Does)

- Green roof installation costs more than initially budgeted (53.85%, 21 Not; 41.03%, 16 Potentially; 5.13%, 2 Does)

- Green roof doesn't offer aesthetic benefits to building occupants (56.76%, 21 Not; 35.14%, 13 Potentially; 8.11%, 3 Does)

- Green roof impedes resale of property (51.28%, 20 Not; 25.64%, 10 Potentially; 23.08%, 9 Does)

- Green roof increases insurance rates and/or limits insurance availability (53.85%, 21 Not; 35.9%, 14 Potentially; 10.26%, 6 Does)

- Green roof reduces access to mortgage financing (48.72%, 19 Not; 35.9%, 14 Potentially; 15.38%, 6 Does)

- Green roof return on investment fails to meet target (48.72%, 19, Not; 39.46%, 15 Potentially; 12.82%, 5 Does)

- Green roof fails to filter air and/or water pollutants before draining (48.65%, 18 Not; 43.24%, 16 Potentially; 8.11%, 3 Does)

- Green roof has a negative effect on property value (39.47%, 15 Not; 26.32%, 10 Potentially; 34.21%, 13 Does)

Appendix C:

SURVEY #2

Retrospective Measure of Green Roof Failure

Survey Population Details

See Chapter 4, Part II for details regarding Survey #2 survey population.

Survey Instrument #2

OWNER & MANAGER Green Roof Assessment

Introduction

Thank you for confirming that you are the person who manages the green roof at this location. Responses you provide about *this particular* installation will be analyzed with other responses in a master's thesis and potentially published in industry journals. We guarantee the confidentiality of your responses. Nothing will be attributed to you personally, and the location of the green roof you manage will remain anonymous. Given this guarantee of confidentiality, are you willing to continue sharing information about the green roof you manage with the graduate student pursuing this research?

Details Regarding the Green Roof at THIS ADDRESS

First, I'll explain the purpose of this survey: the grad student who created it is studying success and failure in green roofs. Understanding temporary and permanent failure, in particular, increases the beneficial outcomes of vegetated roof designs, installations, and maintenance. It also enhances incentives and construction standards for green roofs offered by agencies like the City of Portland. Your responses support industry development and important benefits that green roofs provide to people and the environment. It also establishes an estimated rate of green roof failure, which is currently undocumented.

For us to count failure accurately, we ask that you refer to the green roof at this address only.

4. Please agree, or disagree with one or more of the following descriptions, which define your association with the green roof at this site.

- ☐ I am **the owner** of the building at this address.
- ☐ I am **an occupant** in the building at this address.
- ☐ Excluding planters, I provide the the **building and green roof structural repairs**.
- ☐ Excluding irrigation, I provide the building's **mechanical repairs**.
- ☐ Including **plant replacements, fertilizing and pruning**, and excluding irrigation, I provide green roof **plant management**.
- ☐ Including system repairs and replacements, I provide green roof **irrigation management**.
- ☐ I have another role...

[Please describe your other role...]

Value and Number of Green Roof Repair Events and Reinstallations

9. This question references the industry's average cost of "$15 to $20 per square foot for all types" of green roof installations. Using a square foot monetary value, *OR* a percentage of total green roof cost (from values we will provide), *how do YOU define "major" repairs, as needed to achieve the intended functions of a green roof, separate from the roof on which it is built*?

	Choice of SqFt Values:	Choice of Percentage Values:
As a PER SQUARE FOOT value, only.		
As a PERCENTAGE OF TOTAL green roof value, only.		
As a COMBINATION of SQ FT & PERCENTAGE values.		
Some OTHER value: *[SURVEYOR: enter answer in COMMENTS]*		

Your comments regarding this question are anticipated:

10. Using the values you have just provided, within the first five years of green roof installation, did the building roof *under the green roof* at this address ever require MAJOR UN-INTENDED REPAIRS? If "YES", to the best of your knowledge, how many times has the BUILDING's primary roof received MAJOR repairs within the first 5 years of the green roof installation?

- ☐ I don't know.
- ☐ No MAJOR building-roof repairs were required.
- ☐ Only 1 MAJOR building-roof repair was required.
- ☐ 2 MAJOR building-roof repairs were required.
- ☐ 3 MAJOR building-roof repairs were required.
- ☐ 4 MAJOR building-roof repairs were required.
- ☐ More than 4 MAJOR building-roof repairs were needed.

Comments are encouraged, especially if more than 2 major repairs were required before the building-roof fulfilled it's role.

11. For this question, please differentiate between green roof REPAIRS and RE-INSTALLATIONS, and consider only those problems where the green roof, (separate from other building features) is the primary point of the repairs.

Within the first five years of installation, did the original green roof (*not including the underlying roof at this address*) ever require MAJOR UN-INTENDED REPAIRS? If "YES", to the best of your knowledge, how many times has the green roof received MAJOR repairs within the first 5 years of being installed?

- ☐ I don't know.
- ☐ No major *green roof* repairs were required.
- ☐ Only 1 major *green roof* repair was required.
- ☐ 2 major *green roof* repairs were required.
- ☐ 3 major *green roof* repairs were required.
- ☐ 4 major *green roof* repairs were required.
- ☐ More than 4 major *green roof* repairs were needed.
- ☐ We gave up trying to repair the green roof and left it unrepaired.
- ☐ We gave up, and removed the green roof entirely.

Comments are encouraged, especially if more than 2 major repairs were required before the green roof operated as intended.

Need for Reinstallation

12. Did *any* part the *green roof* (separate from the *roof beneath it*) at this address *ever* require *complete RE-INSTALLATION before the green roof* functioned as intended? If so, how many green roof re-installations were required?

- ○ I don't know
- ○ No re-installations were ever required
- ○ 1;
- ○ 2;
- ○ 3;
- ○ 4;
- ○ 5;
- ○ 6;
- ○ 7;
- ○ 8;
- ○ 9;
- ○ 10.
- ○ We gave up/removed the GR

[Unsolicited Comments]:

Green Roof Satisfaction

14. On a scale of 1 to 5 (1 is low, and 5 is high) please rate your overall satisfaction with the *ORIGINAL* green roof installed at this address.

N/A - I'm not familiar with the original green roof	1	2	3	4	5
○	○	○	○	○	○

[Unsolicited Comments]

15. On a scale of 1 to 5 (1 is low, and 5 is high) please rate your overall satisfaction with the green roof *currently installed* at this address.

It's the same as the original green roof.	1	2	3	4	5
○	○	○	○	○	○

[UNSOLICITED Comments]:

16. Given what you know and have experienced, choose one of the following statements regarding future purchase or ownership of another building that includes a green roof, which best represents your perspective.

- ☐ "I greatly value green roofs, and ***would*** seek them out in future building purchases, or add them to buildings I own."
- ☐ "Depending upon the history of the green roof, and other risks, I ***might*** purchase a building with a green roof."
- ☐ "Due to the risk and/or expenses, I am ***less than likely*** to purchase a building with a green roof, or seek out a building that includes a green roof."
- ☐ "I would ***absolutely not*** buy a building with a green roof, and would ***never*** install one."

[Ask for Comments]:

17. Please tell us about what you have learned about green roofs as a result of your management of this and any other green roofs.

Survey Summary

You've been helpful in relating your experiences! Thank you for the time and insights you have shared to enhance the environment AND the green roof industry!

* 18. Moving towards the last question... Based on the answers you have provided, it may be helpful for us to cite specifics or to quote you. At this point would you be willing to waive your survey confidentiality to allow that? If you're not willing, we will continue to guarantee your confidentiality and maintain your anonymity, including your identity, contact information and all responses. Similarly, unless you allow us to mention your green roof installation, only a count of green roofs meeting criteria identified in the survey will be analysed. Are you willing to allow us to quote the information you have provided, or mention the green roof that you manage? Please agree or disagree with one of the following statements relative to your anonymity, and that of the green roof you manage:

- ☐ Yes, I am willing to waive my personal anonymity and you can name and quote my responses.
- ☐ Yes, I am willing to waive the anonymity of the green roof at this location you can mention it in your report.
- ☐ No. I'd prefer to maintain my personal anonymity.
- ☐ No. Do not mention the name or location of this green roof in any way that identifies it.

19. Since you are willing to waive your confidentiality, please provide:

Your Name:	
Your Company Name:	
Your BEST Cell/Tele #:	
E-MAIL (if possible):	
Times/days of the week when you're most easily reached:	

20. If you have additional insights about green roofs beyond the details asked in this survey, you're invited to contact the graduate student who developed the survey. Anna Thurston: phone 253-227-4923; e-mail thurut(zero)4@evergreen.edu.

We DO have 8 additional *on-line* questions *not required* for completion of the survey that provide more context and detail to our analysis and understanding of green roof failure. These relate specifically to green roof design, installation and management. The time required for this section is ~15 minutes. Would you like us to provide you a web-link to that survey?

- ○ Yes, I'm interested! My e-mail address is: *[SURVEYOR: enter it in the comment window]*
- ○ No, [SURVEYOR: Thanks again for your time!}

E-mail Address:

End of Survey Instrument

Respondent Comments – Survey #2

Questions pertinent to the evaluation of Survey #2 include: questions numbered 9, 10, 11, 12, 14, and 15. These are the questions that provide GR owner, manager, or representative feedback regarding specific GRs in Portland, Oregon. These questions are summarized below. Bold fonts in answers highlight details summarized in thesis discussions.

Question 9: Respondents' Defining Value of a Major (GR) Repair.

"This question references the industry's average cost of "$15 to $20 per square foot for all types" of green roof installations. Using a square foot monetary value, OR a percentage of total green roof cost (from values provided), how do you define "major" repairs, as needed to achieve the intended functions of your eco-roof, separate from the roof on which it is built?"

Respondent Comments Regarding Value of a Major Repair. (bold text highlights coded issues)

1. "Answer requires knowing how much it cost up front…"; $175K to install original GR; $40K to repair.
2. "Too many variables to provide a value." Respondent hasn't had issues with their GRs.
3. "Difficult question."
4. Gazebo GR estimated cost was free (a donation); built in the 40's. Another, more standard building asset, is being allowed to follow natural progression of soil, moss, and plant build-up. Maintenance is required only when tree branches dislodge shingles.
5. "I don't know."
6. **"One must see entire time frame; it's hard to generalize because of variations in GRs**." Consultant evaluated what caused problems; created long-term options + plans for repair. Potentially cascading issues started with building issues (i.e. HVAC failure). Entire GR needed replacement, OR **changes to make the GR less vulnerable. Process took 2-3+ years to implement. Cost to remove, reinstall,** (only at night, can't disturb occupants...) was prevented. Metaphor for **poor design and technology: "Lemon"** (purchase came with multiple issues that only become evident over time. After fixing one thing, the next thing failed, and on, and on...).
7. Respondent stated $.50/sq ft stated because GR is so large. "It's all relative. We haven't had to do anything." Respondent needs to maximize work load. Has provided GR plant, media, irrigation, maintenance research: self-permitted, self-installed the GR with help from a preferred GRP. Can get higher-pay work elsewhere, but is tied to long-term care.
8. The GR is a 3-yr old; cost ~$28K (including sub-roof on new building). GR/membrane keeps water out! Survey participant stated, "other non-ecoroofs are failing."
9. Respondent is "not involved in payments," no reference to another person or a dollar value. Installations are all very small. Process is problematic because they leave behind un-funded maintenance issues, (i.e. weeds). **"GR represent an un-funded mandate."**
10. Respondent "doesn't have authority to [know or] offer a value"
11. Respondent is "…strongly in favor of the benefits provided by GRs" Couldn't readily ID a dollar value, and is "willing to repair regardless of cost because of [reduced heat absorption} and related temperature difference" Respondent assumed repairs would not include a major over-haul without the benefit of available funds.

12. **“A major repair value would equate to "~$1,000.00…" for this GR.** [NOTE: **When people know value of the GR, they reference it and have an answer to this question.]**
13. Answer based on $3/plant/sq ft accounting; **$3 = average cost of a single 1-gallon plant.**
14. Respondent is in their 20's and has no reference exposure to construction costs, or budget management. Respondent is also **a stated GR proponent** having studied the environmental benefits available.
15. Respondent wanted to distinguish between area of repair vs entire 4000 sq ft GR fix. **Anything over $1500.00 would trigger concern**. Spent $30K to install it (~11/sq) : COP provided **$5/sq ft incentive** for 5,000 sq ft of GR.
16. "**The average GR value [promoted] is insanely high/ridiculous.... Systems being provided are over-engineered."** This GR cost ~$5.00/sf (not including the membrane), and he's got enough media to give him trees and plant variety... "**a more simple program sh/could be ~pursued**." He can't see the need for major repairs happening to him. As with others, this was a difficult Q for him to respond to.
17. Respondent stated, "anything over $20/sq ft would be a red flag." A re-do of HVAC housing left debris on top of GR for 1 yr. **Building management took precedence over GR. Respondent also likes the "no maintenance" aspect of the current GR, but it doesn't meet original goals: aesthetics.**
18. Respondent hasn't had to pursue major repairs on this roof, so had a hard time answering the question. **Given a large GR, respondent ventured the least cost.**
19. NO problems answering question. “~**$70K for total re-do, at 9 yrs after 1st GR installed. Removed substrate and membrane. Installed new membrane, root barrier, drain mat, new soil "composite" to a lesser depth (2-2.5"; was ~6"); sedums used instead of native grasses (fescues, sedges, rushes). Roof originally puddled; plants failed to thrive because of limited drainage, compacted, nutrient- and air-deprived soil matrix. [NOTE: Owner is an "early adopter" of GRs]**
20. **Area involved in failure was 25% of the GR. <u>CONTEXT</u> is educational: (2,800 sq ft); 11,000 sq ft Total GR [NOTE: Owner is an "early adopter"]**
21. Respondent referenced a $2-3K total expense as a "major" cost **(~$1.50/sq ft)**; choice based on prior costs and financial thresholds requiring authorization by owner. **** Respondent** was reflecting owner's perspective when answering questions. **[NOTE: Owner is a dedicated "early adopter" with ample financial resources]**
22. No issues answering the question. Data entered; no comments.
23. **Replacement cost** was the respondent’s best-guess answer. Considering re-install of ~10 yr old GR. Requires moving planters, interrupts needed plant production. **Paths on GR specified by landscape architect were not followed by visitors; exposes membrane to UV + foot traffic (uneven wear)**. Asphalt roofs expand/contract w/ heat/cool, daily.

Items, especially non-compatible plastics, permanently embed via chemical interaction with asphalt; "resolved it with a poly-pro liner."

24. Respondent’s value would equate to "~$1,000.00" for this 8' x 10' GR.
25. Respondent wasn't familiar with original GR cost; “makes it hard to relate...”
26. No problems answering this question.
27. "Facility will spend what it takes to keep the eco-roof going." Costs eventually vetted, but respondent is committed to keeping the City’s sustainability demos going.
28. "When there's a lot of other roof-top details (sky-lights, irrigation, walking paths...) there's LOTs to lift or work around to get to the roof if the membrane needs a fix." [NOTE: **Respondent is a dedicated "early adopter"]**
29. **Leaks are the major repair issue** experienced; these **typically require removal of the GR to repair**. Structures are built to last 50 years; issues would indicate the need for a remodel."
30. Value provided based on sq ftg of entire 2-roof installation. **Respondent is happy to let it be weeds**. Would be more involved with GR care and **more concerned with costs IF** they had spent MORE money; respondent chose lower end of average GR cost: $5/sq ft.
31. "GRs are the only way to go. They look good, they help the environment, they do other things too."
32. Respondent has had “no major issues with their 2012 installation.
33. They've not had any repair needs.
34. Haven't needed to repair current GR. ***** Owner is not into the effort/expense; no space / building facility for additional installation. Respondent was otherwise a GR proponent.
35. $10K is respondent’s spending threshold; it's the point at which they would require a second signatory.
36. Respondent represents a NGO; **more than $1/sq ft would be a big concern**.
37. Respondent stated, “Ours is a basic installation (white volcanic scoria w/ sedums; hose for watering via sprinkler attached to a soaker hose.”
38. Respondent stated the “erosion on wood fascia was only low-profile issue. GR was installed by volunteers under leadership of a volunteer who knew his stuff.” COP **incentive** covered costs; they came out ahead, financially.
39. Respondent had a hard time choosing an answer for this question. Because they are a non-profit, they must keep expenses low!
40. Respondent stated, "Any cost would be a major repair. This includes repairs for anything other than plant maintenance."

41. **Respondent would choose 2.5 on Likert scale; caveat is that respondent knows about adding costs for watering and for landscape maintenance; due diligence for membrane installation, testing... Wants to have those #'s before another install.**
42. Value chosen by respondent is based on of the size of the GR installed.
43. Respondent's GR is only 14 months old. Entire cost $66K; $3,300 maximum expense is allowed for repairs. Equivalent to ~$1.50/sq ft.
44. Respondent derived the value from the average cost ($15-20/sq ft) of the GR installed.
45. "Installation was a BES demonstration of what could be done." [NOTE: I**nstallation is TRIVIAL** - **not** a good example because it is tentatively installed on the eaves of the building. Doesn't convey trust in membranes; lack of maintenance results in poor aesthetics, which further takes away from the demonstration message.]
46. Respondent's choice was based the value on the total square footage.
47. Was not present when GR went in; answer depends upon owner's opinion. "$5K is a major capitol expense. The GR outcome wouldn't have an effect upon my choice; **it's all about the [ROI] numbers.**"

Question 10: Major Repair of the Roof under the Green Roof within 5 Years of Installation.

"Using the values you have just provided, within the first five years of green roof installation, did the building roof under the green roof at this address ever require major unintended? If "Yes", to the best of your knowledge, how many times has the Building's primary roof received major repairs within the first 5 years of the green roof installation?"

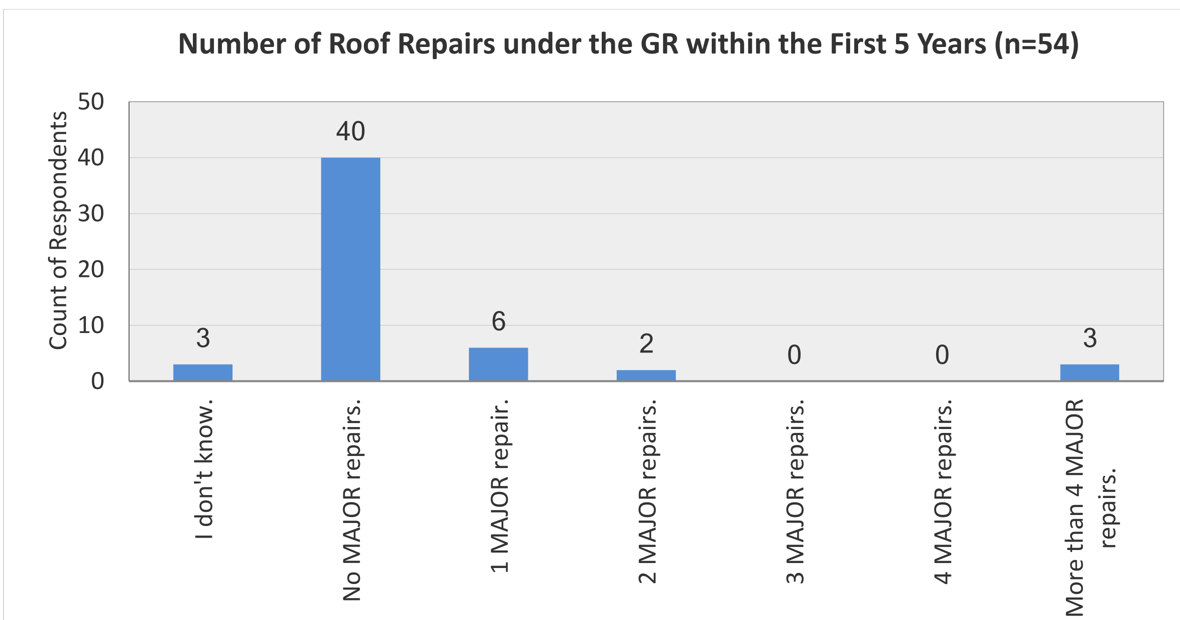


Figure 23. Number of Roof Repairs within First 5 Years

Respondent Comments Regarding Major Roof Repairs.

1. Needed to replace sprinklers; Ag-tape irrigation was meant to get the plants established, didn't last long enough to keep plants going in Portland dry summer. Lots of reflective heat off building that kills plants annually. Not performing as well intended. PVC pipe was used for new irrigation system.
2. Membrane was punctured; unknown occurrence. Did leak test, provided minor repairs.
3. GR is only 14 months old.
4. Membrane was not installed correctly.
5. Repairs were made while GR was under warranty.
6. Some dry-rot happening in 160 sq ft structure installed '07; would use galvanized sheathing or plastic lumber instead of wood.
7. Flashing [design and/or installation] issues lead to leaks.
8. "Our structures are built to last 50 years; issues would indicate the need for a remodel."
9. Respondent's GR is only a year old.
10. GR subject of an irrigation pipe burst; (user-error; the drip system backed-up).
11. Failure occurred after first 5 years (specifically, year 7). Irrigation system was turned off by someone without knowing because of [water-hammer] sound near pump. Grasses installed were also root-bound, and without water, died.
12. Respondent recalled $68,248.00 to complete one re-install in year nine of the installation
13. Stucco re-do on building HVAC housing left debris on tarp on top of GR for 1yr; Building management took precedence over the survival of the GR.
14. The provider fixed Installation defects (membrane seams), within the warranty.
15. All issues were related to the GR, which lacked flashing; and was not well-designed. The roof sagged.
16. Repairs were not membrane-related, usually HVAC systems.
17. Not within the 2.5-year life of the installation.

Question 11: Repair of the Green Roof Within the First 5 Years of Installation.

"Differentiating between repairs and reinstallations, and considering problems where the GR, (separate from other building features) is the point of repairs: Did the original GR ever require major unintended repairs? If "YES", to the best of your knowledge, how many major repairs were provided within the first 5 years of installation?"

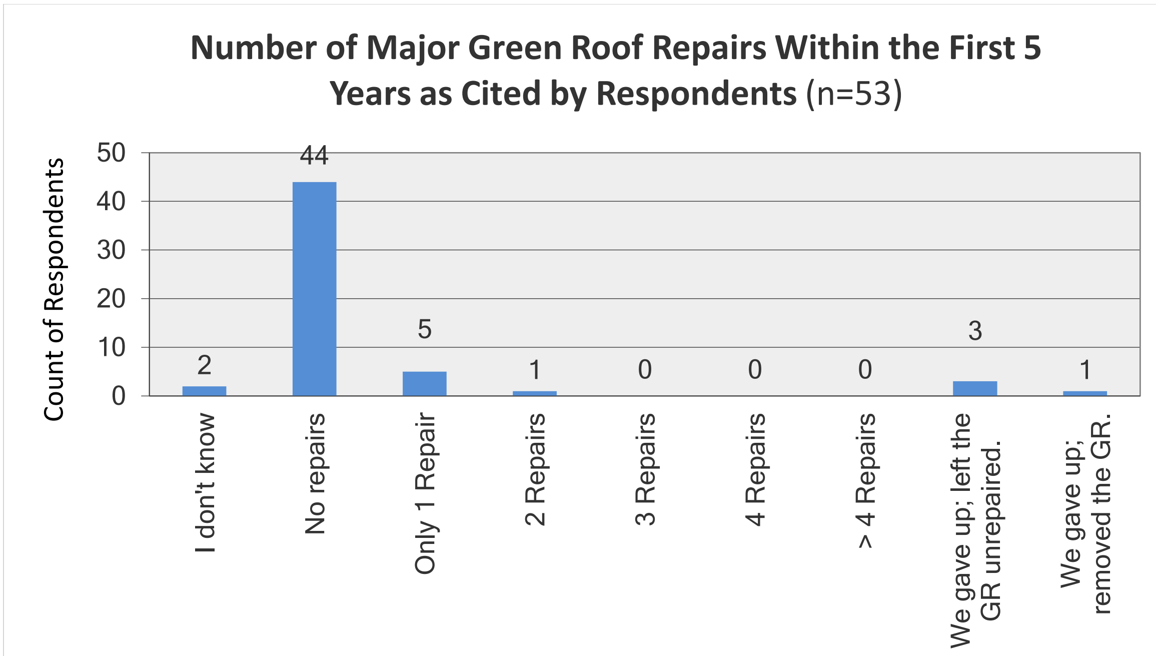


Figure 24. Number of Major Green Roof Repairs within First 5 Years

Respondent Comments Regarding Question 11.

1. Plantings didn't grow; eco-roof is only 2-yrs old.
2. Broken irrigation heads are common because the GR is accessible to loiterers.
3. This answer was qualified afterwards by noting that the sedums for the larger roof died during one of the first hot spells experienced (without irrigation). The owners are OK with the grasses that have moved into the GR. Plants are allowed to thrive or survive.
4. GR manager had to pull up some soil media and membrane to fix burst irrigation leakage.
5. Area involved in failure was 25% of the GR (2,800 sq ft); 11,000 sq ft Total GR.
6. After 9 yrs -GR was totally removed, including substrate and membrane. Installed new membrane, root barrier, drain mat, new soil "composite" to a lesser depth (2-2.5"; was ~6"). Sedums were used instead of native grasses (fescues, sedges, rushes); roof originally puddled. Plants failed to thrive because of insufficient drainage, compacted media, plus nutrient and air deprived soil matrix.
7. Representative respondent is satisfied with the contract maintenance being provided. Crows are the only nuisance because they throw the plants and dirt around. Contractor later solarized same area smothered ~1yr by construction debris to kill clover, invasive grasses (not successful). They gave up trying to eradicate weeds and fixing the irrigation system which has tall risers that are easily kicked/broken (considered “best” irrigation).

8. Owner is horticulturally intuitive; added plants for experimental purposes (daffodils, iris, poppies); has deeper media in some areas.
9. Site was professionally installed. Re-planting was required after sedums died.
10. The sedum plantings repeatedly died. Poor soil biome and is likeliest culprit, along with lack of irrigation during/after establishment in freezing weather.
11. Abandonment by volunteers who maintain green roofs at these sites is common.
12. A 3-yr approach prevented total re-installation; Best value would have been provided by a 5-yr warranty with a maintenance plan. North to South visual aspects can't be uniform.
13. GR was neglected (not maintained), so it got over grown.

Question 12: Reinstallations of the Green Roof

(Question was asked of 8 out of 47 respondents having major GR issues): "Did any part the green roof (separate from the roof beneath it) at this address ever require complete reinstallation before the green roof functioned as intended? If yes, how many green roof re-installations were required?"

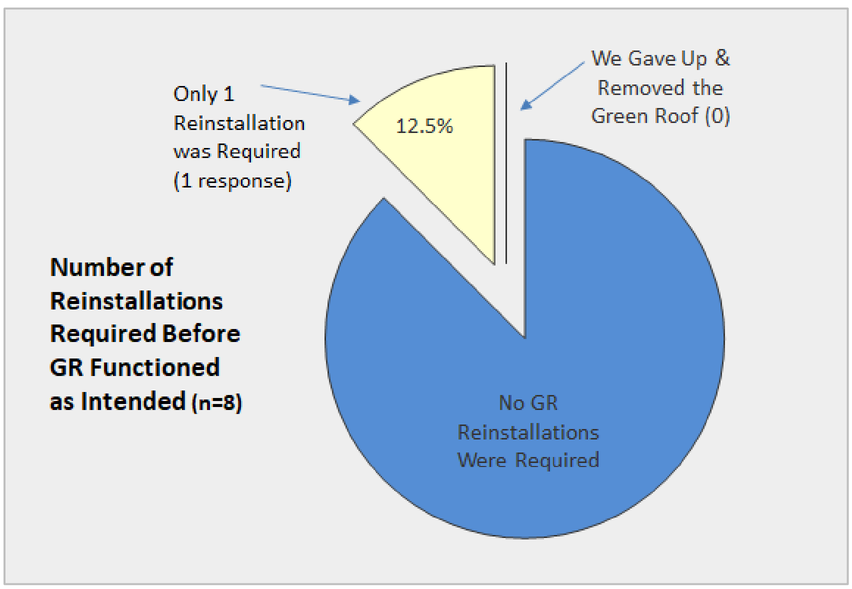


Figure 25. Number of Reinstallations Required

Respondent Comments Regarding Reinstallation of the Green Roof (if any).

1. Plants were re-installed on numerous occasions but soil was never replaced (which is what qualifies as a "complete" re-install).
2. The plant material on the site has mostly died or been taken over by invasive grasses because it is repeatedly abandoned and/or left un-maintained. The site is an un-funded mandate to the maintenance team. Plant dormancy and infill by

invasive/"desirable" species doesn't constitute a complete re-install. But, to the degree that respondent is NOT able to sell management on the lack of fire hazard at this site, they may have to start over because fibrous rooted grasses are not coming out without GR media attached.

3. The reinstallation was an attempted refurbishment. They are still working w/ what's there.

Question 14: Respondents' Satisfaction with Original Green Roof.

"On a scale of 1 to 5 (1 is low, and 5 is high) please rate your overall satisfaction with the original green roof installed at this address."

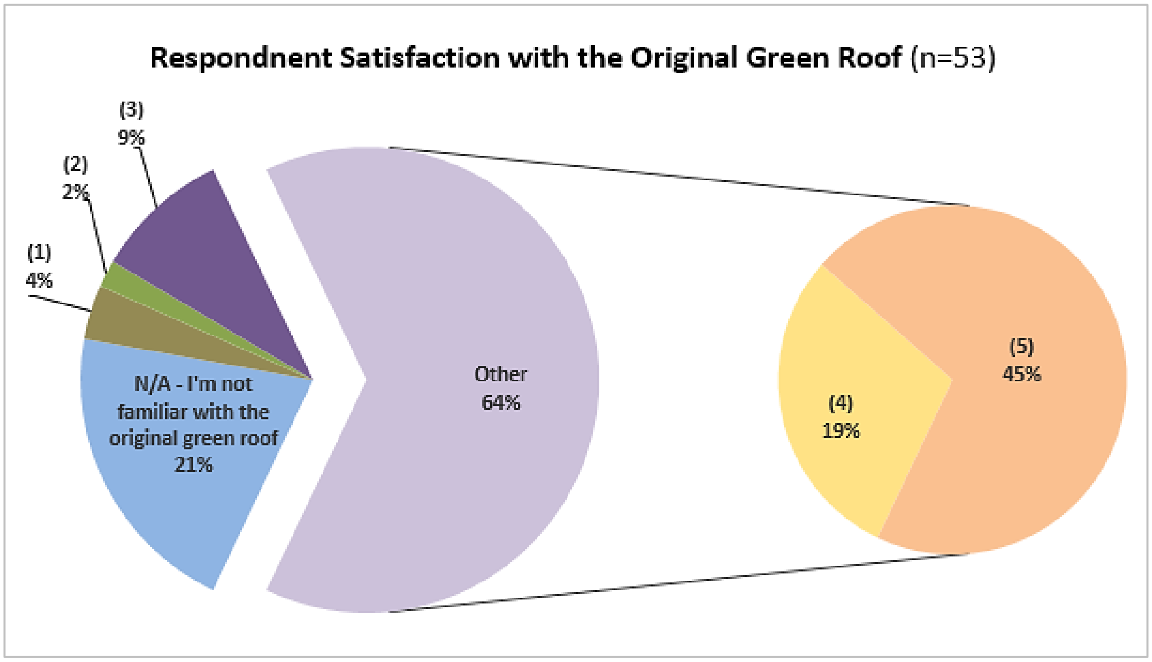


Figure 26. Respondent Satisfaction with the Original Green Roof

Respondent Comments Regarding Satisfaction with Original GR.

1. Installation was a BES demonstration of what could be done.
2. GR is composed of horse troughs with tomato plants.
3. The GR was a quick install with trays that were assembled off-site. It's a steep roof (not many vendors vie for 5:12 pitch installations; only 1-2 offered the necessary warranty). Installation went well.
4. Respondent was "…disappointed by the lack of industry maturation; there's not much of a solid base of information regarding management, plants; after 15 yrs we're still making it up for each building; designers keep changing their minds. Lack of

communication regarding problems is to be expected, but prefers aesthetic plant choices. Response doesn't address maintenance, which is similarly problematic."

5. For what they want to do with plants, the habitat is limited. The growing media used didn't meet our satisfaction for the amount of produce/acre we wanted to grow.
6. Maintenance is intensive! It involves plant replacements and weeding, 2-3x/year.
7. Respondent chose 4.5 – 5 on scale because it was hard to quantify what the GR does. Either you like the aesthetic or you don't. this one supports rainwater harvesting nicely.
8. We have had no problems with the GR although it needs maintenance… We hadn't thought about the maintenance issue while we were chasing LEEDs platinum status for the rest of the structure.
9. Respondent was aware of "tiny flaws" (e.g., wood decay). Their long-term concern had more to do with the need for people to look up to see the GR (especially in spring when flowers are blooming).
10. Trivial issues after GR installation was complete were noted: (i.e., over-spray on bldg).
11. Respondent was "…surprised by the need for summer irrigation; but not necessarily sold on the need for irrigation, or the need to keep the GR green.", they were, however, hoping a non-irrigated GR would work. Their installation only has 3.5 inches of growing media.
12. "Everything seemed OK, except for the amount of extra work, the safety issues, and the need for irrigation that became apparent. Some safety issues were not addressed in design, or were missed in the construction phase." Eco-roof was built via low-bid contract with a 1-year guarantee.
13. Respondent indicated they had a good design, and installation, but they were not entirely successful with plant establishment ("needed to add more sedums").
14. Respondent hasn't had success with GRs that don't use succulents; grassy "prairies" require <u>lots</u> of maintenance to establish and to keep looking good.
15. Respondent recently took GRHC GRP training. Now he's seeing problems with the original GR design (counter flashing openings may compromise the roof leakage/integrity; sloppy installation; and lack of inspection).
16. Respondent had issues related to warranted weed barrier mis-installation.
17. GR was designed with approved funding for graduate student capstone projects, with the understanding that student volunteers will come and go.
18. Weeds are the reason respondent chose lower score: Keeping the GR "established" requires regular maintenance (especially for a rental with a tenant he wants to keep.)
19. Younger respondent was not impressed with GRs; they were someone else's idea.

20. This respondent likes the way his GR "Keeps the water out! I can't say enough about that considering other non-eco roofs that I handle are failing."
21. Respondent saw the specifications and desired outcome for a site they were called as a consultant to assist. The owner couldn't possibly achieve the intentions given what was provided.
22. Respondent indicated a "nice install when it went in… but a lousy drip system undermined results."

Question 15: Respondents' Satisfaction with Current Green Roof

On a scale of 1 to 5 (1 is low, and 5 is high) rate your overall satisfaction with the green roof currently installed at this location.

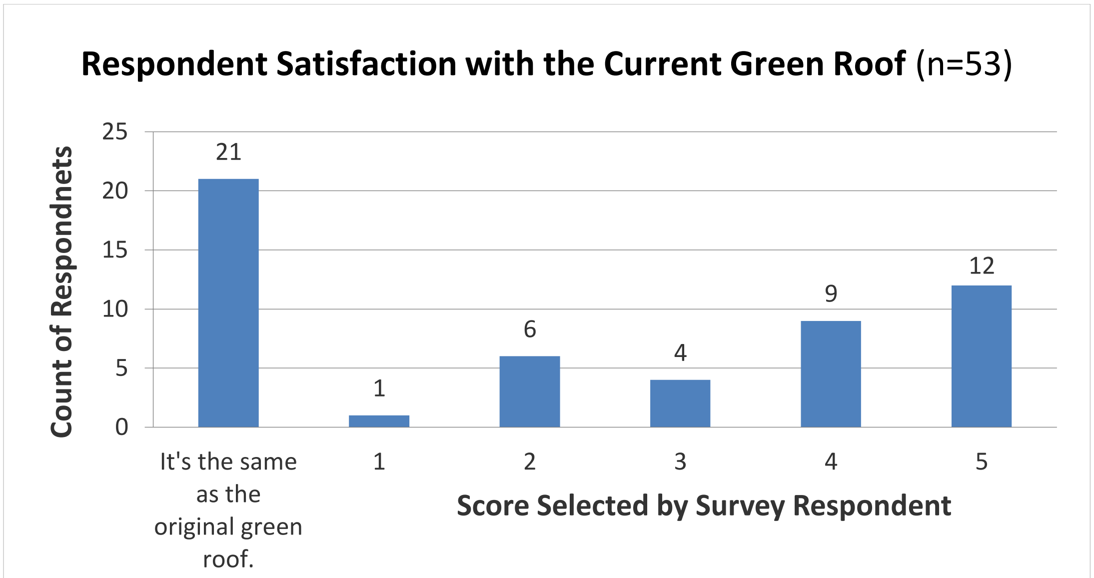


Figure 27. Respondent Satisfaction with Current Green Roof

Respondent Comments Regarding Satisfaction with Current GR.

1. Maintenance is chief issue; concerned with use of potable water to irrigate the GR.
2. Respondent indicated their perception that "some benefit exists from the light growth of remaining plants; It's not a complete waste…" Their GR provides no access to tenants although some apartments have eco-terraces.
3. Respondent noted their "…lack confidence about the long-term GR maintenance and the longevity of the roof's membrane based on recent input from a 'flaky' roofing contractor."
4. Respondent indicated they "…lacked an operations and maintenance plan. These should be given to each customer. The city could also put out a newsletter/e-mail with tips."
5. Respondent "has managed to fine tune amendments and nutrient availability using compost and manure, aiming for approximately 5%/application [need to clarify re: weight, volume, or analysis].

6. No problems; some weed germination from birds.
7. “The GR has lost value with age; it needs attention, and doesn't really enhance nursery plant sales.”
8. Irrigation over-spray was fixed.
9. Respondent indicated that the GR works; especially storm drainage retention; replaces impermeable development according to COP stormwater directive (i.e. GRs are to be installed on all facilities where possible.)
10. Some freezing of the older irrigation system occurred, but not during coldest weather; might not have been drained as well as needed." "it's a shared facility with shared responsibilities. The shared aspect makes management of this GR harder."
11. Even "fully established, the GR requires more maintenance than" the respondent appreciates. The layout involves a grid of plantings mixed with pavers; therefor "extra maintenance of the pattern is necessary to maintain the aesthetics, and is required…" [because the GR is visible to the occupants of the building(s) around it.]
12. Respondent was “…very happy with the selection of sedums installed. It is very aesthetic, and easier to maintain…” [than a mixed species alternative].
13. Respondent couldn't imagine spending $75 K to replace the small GR” with which the survey was associated. Funding was originally provided by a public organization.
14. Respondent hoped that the new building owner would be amenable to re-roofing for continuous GR coverage, because complete membrane coverage wasn't part of original design for urban agricultural production of food.
15. Respondent indicated that the owner “really likes the GR…” because it expresses their environmental values to the community and their customers. Respondent felt hassled by all the contract enhancements.
16. Respondent indicated that "…the amount of maintenance required is still higher than we bargained for at the onset of the installations." "Weeds and trees take advantage of the deep non-standard roof-media and the irrigation. Irrigation is needed to beat 100 days of no-rain periods experienced here."
17. Respondent stated that the GR is “…still not the aesthetic roof they were originally sold. Roof has a border of "river rock at" margins to keep dirt away from walls. Sedums are cheap and readily available locally, and easily self-propagated (a sustainable objective of the GR owner). The GR is a "work in progress". Drainage problems may be associated with "inconsistent feedback on current decline of plants." Getting visitors to understand that the GR is still functioning because of the protection of membrane, and storm drainage protection provided is an on-going effort.” [Visitors are expecting more aesthetics.]
18. Respondent indicated that "…weeds are affecting the aesthetics..."
19. Respondent “likes the "no maintenance" aspect of the current GR, but it doesn't meet BES' original goal of: aesthetics.”
20. Recent heat wave has made it hard to keep the plants alive on this respondent’s GR, especially because the site is managed by a contractor who only visits on a calendar

basis. GR has an automated irrigation system with moisture sensors. Contractor turned down the water, though, and is now responsible for plants lost.

21. Respondent indicated that because "…the GR is an unfunded mandate it is problematic. The irrigation system is mostly intact, but not used. LEEDs certification limits water application to 2 yrs after installation. Respondent is set to provide soil sample; plant evaluation and nutrient evaluation to management with recommendations for future GR management to offset concerns about fire safety and/or aesthetics.
22. Respondent is planning to re-furbish (not re-install) the existing green roof; and doing deferred maintenance that wasn't pursued since original installation occurred 8 years ago.
23. Respondent/consultant will look at GR again after1 year to measure the value of input toward a 2-3 year repair prospect.
24. After not maintaining the GR for one year, the owner is gradually clearing weeds and replanting.
25. Respondent indicated that their GR "…is not maintained, goes to #=!!, is weedy."

Question 16: Respondents' Future Interest in Green Roofs.

Given what you know and have experienced, choose 1 of the following statements regarding future hypothetical purchase or ownership of another building that includes a green roof, which best represents your perspective.

Table 33.
Survey Respondents' Future Interest in a Green Roof

Answer Options	Response Percent	Response Count
• "I greatly value green roofs, and would seek them out in future building purchases, or add them to buildings I own."	39.6%	21
• **"Depending upon the history of the green roof, and other risks, I might purchase a building with a green roof."**	**47.2%**	**25**
• "Due to the risk and/or expenses, I am less than likely to purchase a building with a green roof, or seek out a building that includes a green roof."	13.2%	7
• "I would absolutely not buy a building with a GR/I would never install one."	3.8%	2

Respondent Comments Regarding Willingness to Consider a Future GR.

1. "A GR wouldn't have an effect upon my choice; it's all about the [ROI] numbers"
2. Respondent "…would want to know if [the GR] was installed correctly… would want to know more about the benefits/values" (including ecological). "I'm cautious."
3. "Depends upon the building itself and the GR construction. Building ~can't~ be sketchy. I see a lot of GRs installed on sketchy structures with faulty membranes. The fallout from these failures gives the industry a black-eye. You can put a GR on a good roof, but can't put a GR on a bad roof."
4. Respondent knows about adding costs for watering and for maintenance; They would pursue "due diligence for membrane installation, testing..." to verify the building doesn't leak before purchasing. Respondent "wants to have those questions answered before another install."
5. Respondent gave a higher than average rating because "the industry is beginning to mature and issues have been addressed."
6. Respondent was less than likely to pursue a GR because "there are 'lots of risks and repairs issues; they had had a dream about the cave-in of the Nth floor ceiling."
7. To this respondent, "GRs are a demonstration of stormwater management. Because rain gardens provide same benefit; they don't need GRs. Would want insulation value, but it would need to be a good financial benefit/return to go there."
8. This nursery manager respondent is not into the effort/expense of keeping up a GR. "There's no space or building facility for additional installations. Respondent was otherwise a GR proponent.
9. The age of the GR and its underlying membrane is this respondent's determinant because he knows a lot about old [less reliable] GR technologies and membrane lifespan issues.
10. Respondent doesn't purchase buildings, but they do build GRs on the structures they own.
11. Respondent appreciated the way the GR"…helps with water reclamation." The GR is one part of many green infrastructure elements that allowed the building to reach a LEEDs Platinum rating.
12. "Maintenance is pretty high on any GR," this "not something" the respondent "enjoys or wants to be required to do."
13. This respondent thinks GRs are "way too expensive."
14. Respondent "wouldn't go for a wholesale pursuit; GRs merit critical review before the investment of money & time!"
15. Two respondents reflected the values that their owners espouse.

16. Respondent supported county-wide requirement to include GRs on all new and re-built structures.
17. Wouldn't seek out a building with a GR" even though respondent considers their mindset to be "eco-friendly."
18. For this respondent, "…a GR is a lower priority relative to other building maintenance concerns" [NOTE: Not everyone feels the same about the program.]
19. Although this respondent was among the first to install a GR during Portland's "pioneering period," they "…wouldn't seek out another because not GRs are all engineered/created equally. The GR gave us LOTS of notoriety/exposure …! Our tenant was a happy beneficiary."
20. This respondent is a proponent and sees the environmental values available.
21. Respondent didn't originally have an interest in eco-roofs. "They are a challenge when flat; they trap a lot of water. He would prefer a >1% gradient to create better drainage."
22. Respondent answered before the last option was read: saying "middle of the road."
23. Respondent values [the ROI of] their GRs, and has many in their real estate portfolio; Is interested in other installs.
24. Respondent is committed to re-furbishing the existing building, but can get higher-pay work elsewhere... It's a long-term commitment with expectations to manage the GR."
25. Respondent thinks "Every building with a flat roof, (like an airbag in a car) SHOULD have a GR!" Respondent reminds designers/clients that "they shouldn't compromise!"
26. Respondent is "not a purchaser, but values green roofs."
27. This elder representative "prefers the no-maintenance route." Respondent appreciates that "Nature rules."
28. Respondent "wants to be involved with planning/construction to better the overall outcome before installing another GR."

Question 17: What Respondents Have Learned about Green Roofs.

Please tell us about what you have learned about green roofs as a result of your management of this and any other green roofs.

1. "[GRs] are not self-sustaining (the original intent). They do need maintenance and water."
2. "[GRs] add a lot of aesthetic value. When well done, they don't require much maintenance either, and they can reduce the maintenance required (i.e. cleaning...)." The pros outweigh the cons. Some areas of the GR are deeper (intensive); a leak occurred in a shallow planting area.

3. “I haven't learned anything other than the plants died. Maybe GRs require irrigation to stay alive.”
4. "[GRs] are technically involved and are not necessarily as simple as I would need to feel more confident. I like to be educated, however. They offer a lot of beauty plus environmental benefits that are worth pursuing."
5. “A lot of people don't realize what they're getting into. Especially with publicly funded buildings; when the facilities managers are given these buildings without funding, the GRs go un-maintained."
6. "Besides general maintenance of weeding and watering... Aside from the decrease in rainwater from the downspouts, there is also less debris in the gutter (tray system catches more dirt; any escaping soil goes to bio-swales below).”
7. “The membrane design, especially in the NW, needs to be fully adhered (bituminous asphalt), these GRs can extend the life of the roof and reduce associated costs.”
8. "Staying ahead of weeds via plant coverage is important! One needs to be generous with the planting coverage and use natives whenever possible because they are easier to maintain in this climate. The succulents definitely help to maintain the aesthetic and aid the function of the solar PV system."
9. [Respondent reiterated may answers from above.] “GRs involve lots of work; needs planning from day-one to accommodate all of the differences provided by trade. Budgeting for adequate cost is important. There is little to no information about leak detection systems in the U.S.; finding knowledgeable people is difficult, especially if they are high wage contractors. Learning about invasive weeds is an on-going education.”
10. "The overall GR program intention is positive, but I don't think [the roof top] is the best value of our effort for localized food production, however. Cool season crops are the most productive in this region's weather but better grown at ground level where temperature is not a concern. [Lack of] media volume and [high rainfall] are limiting factors that [minimize] necessary crop nutrients.”
11. "We value GRs, and we value what they can do for the environment and habitat for misplaced birds as much as what they offer to the building and the people who use them. GRs are islands of respite for birds."
12. "I know that they are a natural insulator..." [not always]. "We use it for passive watering of the landscape below, and it's great for wildlife attraction. The output of [cleaner] air is also beneficial. It's unfortunate that residents don't know it's up there; they can't access it."
13. “GRs are considerably more time-intensive than originally thought (re-planting, weeding).”

14. “I didn't know anything prior.” Respondent’s participation enhanced his construction knowledge and overall interest in GRs. Maintenance was minimal (a plus in his mind), The GR cut down on/insulated noise and temperature changes; Roof was an experimental comparison of 2 depths: thin/thick; he thinks the later performed better. He also became conscious of acorn seedlings from nearby trees because of the need to regularly weed them.

15. “I didn't know anything prior to 2004. Irrigation and weed maintenance are the chief needs.” The GR gives the respondent a lot of community visibility; it is a part of their 501-c-3 mission to be sustainably-oriented.

16. "It's a great feature; a key towards obtaining LEEDs certification. Ours is used for filtration of stormwater before reaching rain gardens below. It minimizes our carbon-footprint "

17. "[GRs] do require maintenance, which is understandable. Putting on a GR without access for the landscaper, however, was very short-sighted." Respondent’s access to the GR is via hatch, and a tall ladder, which also requires “hopefully-used” safety equipment. Respondent "became aware of safety issue only after installation was complete when they needed to irrigate and for plant/weed management."

18. "I think they are a workable solution under the right conditions...; ...lovely to look at."

19. "They're beautiful/extraordinary; and add something special to the value of the roof/property; provide storm drainage/bio-swale benefits, too (most important)".

20. Respondent “has a preference for EPDM membranes.” GRs without automated irrigation become patchy, ~but~ sun-exposed GRs require less maintenance than GRs in a forest setting with irrigation; (*lots* of tree seedlings to pull!). Current GR is accessible to people and easier to fix than the standard GR (because it has no HVAC units to manage). "Knowing that there's more to know" encourages respondent’s involvement, especially around heat loss/gain, and enhanced urban livability because of green spaces.

21. "[GR's] require little/no maintenance once installed and established (took 2-3 yrs before plants filled in)."

22. Lower maintenance than expected.

23. “GRs require more work than we first anticipated... but we're willing to do it b/c it helps us attract tenants.”

24. “I think GRs are great; they add an important aesthetic to the property (i.e. our cafe deck overlooks the GRs and the Columbia river). Biodiversity is also important. Birds and butterflies in the industrial setting are a great addition. Respondent doesn’t charge a higher rate of rent, but lives in a building with high-end GRs in operation below, (allows view of juxtaposition of green against dormant).”

25. “…1) There is difficulty getting contractors to install small foot print eco-roofs. They are more interested in large scale projects. 2) Seasonality of installation is important to success (respondent pursues fall, winter, and spring installs to take advantage of rainfall, and avoid summer because of need for irrigation and poor contract management of irrigation when they have to take this route). 3) Portland’s stormwater management division commonly asks Parks & Rec division to maintain their GR installations for 2 years. After the 2 yrs, it is difficult to get contract management to pick up on the small projects. 4) Agency stations require stand-by generators, which burn plants growing w/in 3 feet of exhaust. Respondent has learned they don't need to replace lost plants because they readily grow back on their own. Spark arresters are otherwise installed on venting to minimize fire hazards. Buildings are built of concrete or steel (without wood) because of exhaust generator fire hazards, but GR are not a fire hazard.”
26. “Green roofs are high maintenance, and expensive to start, but totally worth it. One needs to select the right ground cover right away, however, (nothing that grows too aggressively!)”; Respondent installed a better choice after one season of needing to mow what was originally installed.
27. "Delegation of responsibilities is important, especially given limited access to the eco-roof and the technical aspects involved with the irrigation system.”
28. “We are pushing in the direction of more eco-roof installations, but the ownership of one requires effort. The portion of the building that has the roof is not as noisy when birds are dropping stuff."
29. "[GRs] require more maintenance than I originally anticipated. Access is also a big issue (we use 40' extension ladders that require tie-offs, which we fortunately had built-in. We have however, retrofitted some of the roofs for easier access.” “Plant materials (specifically, native shrubs that were densely planted) on deeper roofs tend to invade the building flashing.” Rain shadows because of the building are also a problem. These are managed by removing the plants, replacing them with gravel. Sedum cuttings installation on 1 sub-surface irrigated roof was a short-term failure. The plants did eventually take hold, but it was only after the first season. Installation timing [in November] may have contributed to the problem (wet/prolonged deep freezes at this time of year will kill lots of water-based plants, especially if they are not yet rooted.)
30. "Most of our GRs are not visible; they are therefore easily forgotten, and as a result the plants can be lost. Access is also sometimes difficult/dangerous. This GR came with ladder access and tie-offs to meet these safety issues."
31. I didn’t learn anything outstanding; art is costly.”
32. Asphaltic roofs expand/contract with heat/cool, daily. Items placed on top embed themselves, sometimes permanently... Not all materials are compatible with asphalt roofs"

33. Respondent learned that up-keep is more than expected; but the payback has come from accolades earned from COP. The City also gave them incentives and a tax break, (even though respondent thinks they would have installed the GR without these benefits). Respondent ~could~ charge more because of the GR, but technically cannot it's a Title 8 (low-rent) facility.
34. The eco-roof "definitely requires particular plants. These are not the average flowers or grasses one would use in a garden!"
35. Respondent now knows a lot more about plant species and climate soil/soil-depth and climate differences (these become evident on elevated GR's and are different across the country). Respondent purposefully pursues failure analysis as a way to minimize failure in the future.
36. "It's important to tell visitors the reasons why the GR is installed, especially given the lack of perfection in aesthetics; many components make it fully successful. Plants/aesthetics are only one component."
37. "GRs are pretty easy to take care of. People like the looks, too; they ask to see it when asking about rentals." Not sure that the GR would add value to the rent price: they can't charge more because they provide City-chartered "affordable housing." They "don't allow people on it for liability reasons, and reduced maintenance," but respondent knew of "apartments downtown that do allow access which likely add lots of value to the rent charged."
38. 1.- Don't let it go to seed (for more than 1-2 years); 2.- Even without maintenance, it is visited by many pollinators and birds.
39. [GRs] can be installed more simply than what's promoted, and for much less than is promoted. It can seem daunting for the uninitiated, though. Getting at the repairs is the biggest likely problem, but the GR is meant to protect this investment.
40. "I'm honored to tell others about GRs!" (respondent also admits he's evangelical about them). He knew nothing prior... Major learnings: 1) "It would be extraordinary helpful if energy savings could be pre-determined..." (prior to financial commitment and to construction). You can obtain more certification points for the energy savings. 2) GRs provide a great marketing tool for future tenants (utility savings); 3) Soil depth, drainage mats and membrane coverage issues due to shrink and swell are minimized by lack of UV exposure. "That's a Huge Deal!" Maintenance is more than a traditional roof, but was part of the COP/BES incentive program and he was willing to accept it. Tenant pays for both utilities and landscape contract maintenance. Neighbors appreciate the view; "It's hard to measure this value - and not a viable selling point."
41. Media must be chosen to fit plantings. A continuous maintenance plan is appropriately selected and followed for performance, not just aesthetics, and it must include irrigation if one plans to keep it green (usually where there is access to people).

42. Respondent knew a little about the thinned GR inherited as management responsibility. Sedums were replaced with a short single-stemmed grass that re-seeds; grass is impossible to remove w/o soil removal in fibrous root system. Respondent must limit his efforts to paid work orders"

43. “[GRs] require minimal maintenance. GR helps property value; from a landlord perspective, it made the building more attractive, but not necessarily for a higher rate of rent, and despite tenant's lack of appreciation (which might have translated into tenant care of the GR). Respondent installed a GR at home and is a cautious proponent. Unique installation at home allows further testing. "May have made money because of $5/sf incentive."

44. Stormwater management incentive started the process. "Temperature benefits are fantastic! Ease of maintenance is a plus... as well as little irrigation needed. [NOTE: respondent is horticulturally inclined and comes from a construction background]; Respondent was impressed at the benefits gained; is a true convert; will be repeating the native plant installation of landscape; would install a GR if he had a budget at home...

45. “The technology isn't there yet..." wished for better use of tax-payer funds; suggested letting “the builders experiment and bear the cost.”

46. GRs become a facilities liability that we don't actively support. Creates friction with volunteers (parents) who end up leaving behind "legacy projects" that Facilities Maintenance is then liable to maintain. ""Legacy installations" by volunteers used to be the rage.”

47. "I know, via work, the basics of GRs, and what they do. The best thing is, I don't have to do much [maintenance]. A leak would be a pain in the butt, but it doesn't make me shy away from using GRs as a great marketing tool for our Platinum LEEDs certified and non-certified buildings. Sustainability definitely allows us to target the higher end-rental customer.”

48. "They are a beautiful place to sit upon; they host a remarkable number of bugs and birds. The effort is a little over-whelming, however."; Respondent is "amazed" that the roof is doing "something" but when he looks he does find issues to address. He wants to kill weedy grasses; install native grasses; install better drip irrigation; knows it is going to "brown-out" /go dormant...

49. “Americans are far more focused on the ROI/profit than the environment; The GRs are needed in order to protect/preserve!”

50. “[GRs] don't survive and thrive without maintenance, particularly in the first 2-3 seasons. They need watering the first 1-2 seasons, but this depends on the profile and plants, should be OK with no regular irrigation just supplemental water in very dry conditions.”

51. Living in Texas allowed respondent to learn about GRs. Respondent was “not familiar with GRs in Portland, but they appear to be popping up all over the place."

52. "If installed correctly they do a good job of slowing rainwater run-off, (GR's intended purpose); the water that does run-off can be used to water other landscape features (we have a cistern); GR is visible from street (high priority); GR also helps birds and bugs; we wanted a highly visible and attractive GR."

53. “[GRs] are more expensive than regular roofs because of maintenance. The potential for damage and failure needs to be considered; including the risk for items inside. Increased risk of maintenance staff is a whole added layer (ladders/safety harnessing, etc.); plus, insurance borne by contractor; requires more maintenance and manager oversight - are either party qualified? educated?”

54. [I have learned] “…A LOT! The longer I'm in the trade, the more roofs I’m on, the more I know. Value of GRs is the future of urban construction for lots of reasons (building performance; 2 roof longevity, 1 stormwater, 3 decreases fire risk - if it has a healthy mat of sedums, 4 bug/bird habitat 5) ambient air temp HVAC work better, energy conservation [UHI harder to quantify]...

“*If you can see things out of whack, then you can see how things can be in whack*.”

(Nel, 2004, quoting Dr. Seuss)