MANAGING STORMWATER WITH GREEN ROOFS: FINDINGS FROM NORTH AMERICAN RESEARCH

DVORAK, BRUCE
Texas A&M University, bdvorak@tamu.edu

1 ABSTRACT

Green roofs (vegetated rooftops) are well-known for ecosystem services including retention of stormwater draining from rooftops which helps reduce peak flows and flooding in urban watersheds. Much is known about the functions of green roofs in Europe, but less is known about their performance in North America. This review of literature assesses stormwater retention research from thirty-two extensive green roof field investigations published from 1998 through 2012. The data suggests that in North America, green roofs retain rooftop precipitation in all six geographic regions reported and they reduce peak flows in five reported regions. Across all regions, sixty-one percent was the average amount of precipitation retained. The highest average retention was in the Midwest region at seventy-four percent and the lowest average retention was the Pacific Northwest region at fifty-two percent. There were some regions, however, with large urban populations that were not represented, and some regions had conflicting or inconclusive findings. More research is needed to better understand ecosystem services in some regions and to begin research in regions not represented. Only a few of the studies had landscape architects directly involved with extensive green roof stormwater research. This marks an opportunity for landscape architects to better understand how green roofs function locally. These findings are important because those responsible for managing urban stormwater need to know that not all green roofs perform the same and design characteristics and maintenance practices are important. One should not assume that any green roof will effectively manage stormwater.

1.1 KEYWORDS

green roof, retention, peak flows, substrate, eco-region

2 INTRODUCTION

Before the turn of the twenty-first century, there were only a few extensive green roofs (with < 12.5cm deep substrates) built in North America and perhaps only as many advocates. However, the groundwork that had been laid by a few began to awaken the environmental consciousness of many to the potential benefits and uses of green roofs. In 1998, for example, Bill Thompson in *Landscape Architecture* magazine wrote “Grass-Roofs Movement,” an article in which he discusses the potential benefits of green roofs and how American landscape architects may find creative uses for green roofs in the near future. He writes, “An opportunity is emerging to introduce landscape architecture into another realm—the roofs of buildings—in a revolutionary way” (Thompson, 1998). He elaborated on the multiple benefits of green roof technology already proven in Europe including mitigation of urban heat islands and stormwater management as well as providing habitat for urban wildlife. Bill Thompson was right about landscape architects engaging with green roof technology. Since 1998, the ASLA Headquarters green roof was built (2006), many green roofs have been designed and built by landscape architects, and many projects have been awarded recognition by the ASLA and discussed in *Landscape Architecture Magazine*, and contributed to LEED® certified projects (N. Miller, Spivey, & Florance, 2008). It is evident that landscape architects in professional practice have worked with green roof technology over the last decade. However, aside from professional practice, green roof technology has not been largely embraced by landscape architecture faculty doing research (Blank et al., 2013; Butler, Butler, & Orians, 2011). There may be a need therefore, for those teaching and designing green roofs in North America to understand how green roofs manage stormwater in their region. This study will help address these issues.

In 1999 there were only five European-styled extensive green roof venders accessible in North America (Peck, Callaghan, Kuhn, & Grass, 1999). Today, there are hundreds of vendors representing this fascinating, multifunctional, multi-beneficial, and at times complex technology (Cantor, 2008). Although green roofs have a long history in Europe with several decades of product development and research (Cantor, 2008; MacIvor, Ranalli, & Lundholm, 2011), in North America, green roof systems are still under development regarding products, guidelines and research (Cantor, 2008; Dvorak, 2011; C. Miller & Narejo, 2005).

Regarding application of the technology, there are a number of different types of off-the-shelf green roof systems ranging from pre-planted modular green roof trays to monolithic planted-in-place multilayered systems (Simmons, Gardiner, Windhager, & Tinsley, 2008). There is an emerging body of peer-reviewed research that investigates various green roof applications across North America (Dvorak & Volder, 2010; Getter & Rowe, 2006; Oberndorfer et al., 2007) and the vegetation in one region may not necessarily work in another region. Each eco-region may need green roof research to supplement its industry development and to better understand which ecological services can be effectively realized with green roofs (J. T. Lundholm, 2007).

The reported benefits from green roofs have been mixed as some market-based systems were not as effective as others (Simmons et al., 2008). Comprehensive reviews of green roof research are needed to better understand how they perform; including how green roofs manage stormwater and what design or property characteristics may influence their performance. Current reviews of stormwater research includes results from across continents and context (Berndtsson, 2010). Since the climate and natural vegetation in North America is different from those in Europe and abroad, this study reviews peer-reviewed extensive green roof stormwater retention research that has taken place across North.

3 METHODS

This review of green roof stormwater research begins when original research from North America on extensive green roofs was first published in 1998 through January of 2012. The method for selecting papers followed criteria similar to Dvorak and Volder (2010). To be included the research: (1) was located in North America, (2) applied directly to extensive green roof stormwater hydrology research, (3) was published in a peer-reviewed journal or a refereed conference paper, and (4) was published in the English language. If the paper was published as a conference paper only, then it had to be cited in other peer-reviewed publications or represent an eco-region where little has been published. Green roof research papers regarding stormwater management were collected and sorted into topic areas (water quantity and quality). Stormwater retention and flow reduction findings were sorted by geographic region into tables to recognize their original contribution to knowledge. Distribution of research in North America is captured in Figure 1 which shows the location of the research within one of six geographic regions determined by green roof stormwater research site locations, eco-region and Natural Resources Conservation Service (NRCS) rainfall distribution patterns. An eco-region is a land area identified by its climate, natural vegetative cover such as the Tall-grass prairie eco-region in the central United States and other factors (Bailey, 1996). Green roofs often make use of drought tolerant native or naturalized vegetation such as succulents, drought tolerant grasses and forbs which can be low maintenance and sustained without irrigation in some regions.

Thirty-two peer-reviewed papers were found spanning from 1998 to 2012 within six geographic regions including: Pacific Northwest, Midwest, Southcentral U.S., Eastern Canada and Northeastern U.S., Mid-Atlantic and the Southeastern U.S. region (Figure 1 and Table 1). An “investigation” in this study is the reporting of results from a single green roof design. Some of the papers reported findings from more than one investigation. With Excel software, the reported retention and flow reduction rates from each investigation were separated into tables for each region. Averages and standard deviations were determined and reported in tables. The sample size was too small for more advanced statistical analysis. Three regions dominated the number of investigations including: the Pacific Northwest (*n* = 7), the Mid-Atlantic (n = 7), and the Southeastern U.S. (*n* = 6). Three of the four types of rainfall distribution patterns recognized by the NRCS (formerly SCS) are represented (1a, II and III) across the findings (Figure 1). As can be seen in Figure 1, primarily the edges of North America are well-represented with stormwater management research, but the central U.S. and the west coast is lacking research.

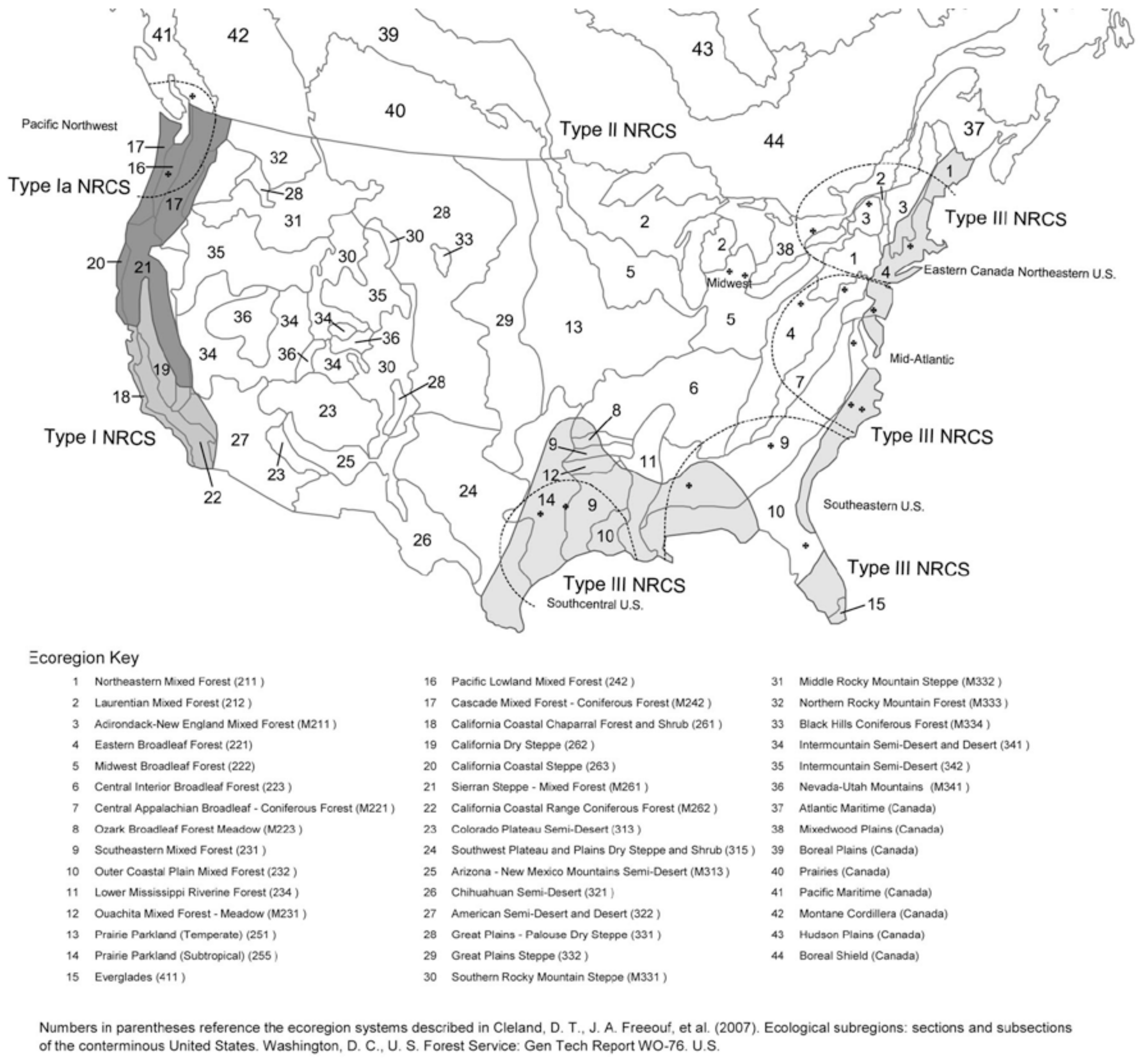

Figure 1. North American green roof research regions based upon site location (dots) eco-region (see key) and NRCS rainfall distribution type (shaded areas). Geographic regions (curved lines) for this study include: Pacific Northwest, Midwest, Southcentral U.S., Eastern Canada and Northeastern U.S., Mid-Atlantic, Southeastern U.S.

4 RESULTS

4.1 General Findings

Some of the early North American research that documented stormwater retention and detention capacities of extensive green roofs in the peer-review method were published as conference papers (Hutchinson, Abrams, Retzlaff, & Liptan, 2003; K. K. Y. Liu, 2003; Charlie Miller, 1998; Monterusso, Rowe, Rugh, & Russell, 2004; Rowe, Rugh, VanWoert, Monterusso, & Russell, 2003). Several of these papers were published by the for-profit group *Green Roofs for Healthy Cities*, an organization set up to investigate, teach and promote green roof technology as part of its annual meeting and exposition conference *Greening Rooftops for Sustainable Cities* and later renamed *Cities Alive*.

Table 1 summarizes the findings of green roof stormwater retention from North America. For all of the geographic regions, green roofs captured and retained precipitation, causing a delay in runoff and peak flow rates compared to conventional roofs as a control. The average percent of precipitation retained across all regions represented was sixty-one percent (Table 1). The average standard error was eight and the total number of investigations was thirty-two. The highest average retention was the Midwest region at seventy-four percent (n = 5) and the lowest average retention was found in the Pacific Northwest region at fifty-two percent (n = 7). The range in standard error was the least in Eastern Canada and the Northeastern U.S. at 4.47 with a sample size of five (n=5). The maximum standard deviation was in the Southcentral U.S. at 26.87 and the sample size was two. In Simmons et al. (2008) there were only three rain events reported; however, data included results from six different green roof systems designs and there was much variance between the green roof system designs.

Table 1 Location of extensive green roof stormwater research site by geographic region, number of investigations and average percent of rainfall retained.

Geographic Region	Number of Investigations	Ave. retention (percent)	Standard error
Eastern Canada and Northeastern U.S.	5	56	4.47
Mid-Atlantic	7	59	12.72
Pacific Northwest	7	52	20.96
South-central U.S.	2	58	26.87
Southeastern U.S.	6	67	10.40
Midwest	5	74	6.96
	32 total	**61 ave.**	**8 ave.**

4.2 Retention of stormwater and reduction of peak flows

All of the papers reported the quantity of precipitation retained. Only some of the papers reported peak flow reductions. Tables 2 to 7 report the individual investigation details by geographic region including the percentage of precipitation retained and reduction of peak flows for some investigations.

The research in eastern Canada and the northeastern United States (Table 2) is represented by investigation sites located in Ottawa, Toronto and Storrs, Connecticut, and are equally divided within the NRCS distribution of Type II and III. The average percent of precipitation retained was fifty-six and the reduction of peak flow ranged from twenty-five to eighty-five percent. The green roofs in Toronto were irrigated and it was reported by MacMillian that the irrigation likely interfered with the green roofs capacity to retain stormwater (MacMillan, 2004). The study by Gregorie, reported that most of the precipitation was snow, even though the study period covered one year (Gregoire & Clausen, 2011).

Table 2 Average stormwater retention and flow rate reduction from extensive green roofs in Eastern Canada and Northeastern geographic region

Research Site Location	Eco-region of Research Site	Ave. retention and (flow rate) % reduction	Major Points Discussed	Study
Ottawa, ON	St. Lawrence Lowlands	54 (-)	Delayed runoff from 19 mm storm, 95 minutes and 85% retained; 21 mm storm delayed 4 minutes and 73% retained.	Liu (2003)
Toronto, ON	Lake Erin Lowland	55 (85)	Green roof was continuously irrigated and media was maintained moist, which reduced capacity to retain rainwater.	MacMilla (2004)
Toronto, ON	Lake Erin Lowland	57 (25-60)	Succulent green roofs with 5% vegetated cover. When substrate was dry for at least 6 days, 1.5 cm rain events were 100% retained and 7.5 cm roof retained less on individual events; both effectively reduced peak flows.	Liu and Minor (2005)
Toronto, ON	Lake Erin Lowland	63 (-)	Continuation of previous study (MacMillan, 2004) with irrigation reduced June through October when moisture fell below predetermined values. Irrigated about every 2 days average. Rainfall was above normal for region.	Van Seters et al. (2009)
Storrs, CT	Southeast New England Coastal Hills and Plains	51 (-)	Succulent green roof trays dominated by *Sedum* spp. retained 41.6 percent of precipitation during the first year of establishment. Majority of precipitation was snow.	Gregorie et al. (2011)
	Region average retained 56%			

The Mid-Atlantic region reports findings from Philadelphia, Rock Springs and Pittsburgh, Pennsylvania; Washington D.C. and two sites in North Carolina (Table 3). The research sites are equally divided within the NRCS rainfall distribution Type II and Type III. The precipitation in the region is primarily rainfall; however, some year's snowfall can contribute significant amounts. The average volume of precipitation retained in the region was fifty-nine percent and the standard error of the mean was 12.72. Peak flows were reduced from five to eighty-seven percent depending upon how saturated the media was prior to the storm event.

Table 3 Average stormwater retention and flow rate reduction from extensive green roofs in Mid-Atlantic geographic region

Research Site Location	Eco-region of Research Site	Ave. retention and (flow rate) % reduction	Major Points Discussed	Study
Philadelphia, PA	Northern Atlantic Coastal Plain	65 (-)	Succulent green roof pilot study was set up to monitor 24-hour, 2-year return-frequency storm events. Storms <1.5 cm runoff was negligible.	Miller (1998)
Rock Springs, PA	Central Appalachian Broadleaf/Coniferous Forest-Meadow	40 (-)	Succulent green roofs with a porous expanded polypropylene layer above growth media, only *Sedum sperium* planted. Results are from two 25-mm October rainfall events.	DeNardo et al. (2003)
Neuseway and Goldsboro, NC	S. Atlantic Coastal Plain	55-63 (57-87)	Runoff from two succulent green roofs were monitored from one collection point. 78% average reduction of peak flow.	Moran et al. (2005)
Rock Springs, PA	Central Appalachian Broadleaf/Coniferous Forest-Meadow	45 (56)	Succulent green roof results from October and November months of data collection, plant coverage 40% to 90% of roof surface, delay up to 5.7 hr. 100% retained <12 mm	DeNardo et al. (2005)
Pittsburg, PA	Pittsburg Low Plateau	70 (5-70)	Extensive succulent green roof retained 70 percent of precipitation from August to January.	Bliss et al. (2008)
Washington, DC	Northern Atlantic Coastal Plain Chesapeake Uplands	74 (-)	Meadow-like green roof on ASLA Headquarters building results for 50 of 65 events, no runoff was detected. Significant delay in water runoff during large events. 2% to 45% slope.	Glass and Johnson (2008)
	Region average retained 59%			

The Pacific Northwest (Table 4) has stormwater research taking place in Portland, Oregon and Vancouver, British Columbia. The region falls within the NRCS rainfall distribution Type Ia. Precipitation primarily falls as rain and the pattern of rainfall is typically light rain falling throughout the rainy season but summers tend to be dry. The average amount of precipitation retained was fifty-two percent, and peak flows were reduced in one study ranging from eighty-four to ninety percent. Although precipitation retention rates were the lowest of the regions, the flow reduction rates during the study were consistently up to ninety percent.

Table 4 Average stormwater retention and flow rate reduction from extensive green roofs in the Pacific Northwest geographic region

Research Site Location	Eco-region of Research Site	Ave. retention and (flow rate) % reduction	Major Points Discussed	Study
Portland, OR	Willamette Valley	69 (-)	Ecosystem maturity, rainfall distribution and intensity patterns, and ambient air temperature appear to influence runoff behavior.	Hutchinson et. al. (2003)
Vancouver, BC	Pacific Maritime Lower Mainland	67 (-)	The succulent green roof showed mean retention of 67% precipitation with the 75 mm deep substrate.	Connelly and Liu. (2005)
Portland, OR	Willamette Valley	50, -, 64 (90),(84),(90)	Hamilton Apartment ecoroof average peak flow reduction was consistently over 90% for the most intense storm events. Annual retention 50% with high of 63% in 2005. Portland Building peak flow reduction 90% for intense storms, 64% overall annual retention.	Kurtz (2008)
Portland, OR	Willamette Valley	18, 29, 69 (-)	Three large ecoroofs investigated for 28 months. Meadow-like designs had substrates 10- 15 cm deep.	(Spolek, 2008)
	Region average retained 52%			

The Southcentral U.S. region (Table 5) green roof research was limited to two locations: Austin, Texas and College Station, Texas. Both sites fall within the NRCS rainfall distribution Type III. Precipitation in the region is typically dominated by intense thunderstorms and infrequent tropical storms. Distribution of rainfall is bi-modal with spring and fall rains. Summers are consistently very warm and droughty in some years. The average amount of precipitation retained in the region was fifty-eight percent. Peak flow reduction was not reported. The research at the Austin site investigated six different green roof designs. Some of the designs did not perform well and therefore the overall average for the site for the three days reported was low compared to other studies (Simmons et al., 2008). In College Station, Texas however, seventy-seven percent of all storms was retained from April to September of 2010. Retention ranged from thirty-seven percent to one-hundred percent. There was a fairly strong negative correlation (R^2 = -0.8038) between the depth of rainfall and percent effectiveness which means that generally the larger the rainfall event the less effective the green roof modules were in retaining rainfall. Rainfalls of one inch depth or less were largely retained.

Table 5 Average stormwater retention and flow rate reduction from extensive green roofs in the Southcentral geographic region

Research Site Location	Eco-region of Research Site	Ave. retention and (flow rate) % reduction	Major Points Discussed	Study
Austin, TX	Subtropical Backland Prairie	39 (-)	Stormwater retention differences were observed between six different vendor systems. Plots were irrigated.	Simmons et al. (2008)
College Station, TX	Subtropical Backland Prairie	77 (-)	Succulent green roof modules received only rainfall. Green roofs retained 36.9 to 100 percent of rainfall. Several large storms occurred during the study including 10cm (4 inches) of precipitation over 24 hours. This is a 2-year storm event for the region and 36.9 percent of precipitation was retained.	Dvorak et al. (2011)
	Region average retained 58%			

The research sites in the Southeastern region of the United States (Table 6) were located in Orlando, Florida, Athens, Georgia and Starkville, Mississippi. The investigation sites fall within the NRCS rainfall distribution Types II and III. The average retention of precipitation was sixty-seven percent and all precipitation was rainfall. One of the research sites made use of rainwater harvesting and attained one-hundred percent of the precipitation during the study period by using the harvested water for irrigation (Wanielista, Hardin, & Kelly, 2008).

Table 6 Average stormwater retention and flow rate reduction from extensive green roofs in the Southeastern geographic region

Research Site Location	Eco-region of Research Site	Ave. retention and (flow rate) % reduction	Major Points Discussed	Study
Orlando, FL	Florida Coastal Plains Central Highlands	80 (-)	Native herbaceous green roof runoff captured in 18 green roof plots to cisterns was evaluated. Retained 80% of rainfall.	Wanielista et al. (2006)
Orlando, FL	Florida Coastal Plains Central Highlands	100 (-)	Runoff from two 10 cm green roofs was captured in cisterns. No overflow from cisterns for year of 109 mm average is 127 mm of precipitation.	Wanielista et al. (2008)
Athens, GA	S. Appalachian Piedmont Midland Plateau	78 (-)	100% retention of small storms, influenced by season, temperature, moisture content of media prior to rain.	Cater and Rasmunssen (2006)
Starkville, MS	Coastal Plans-Middel Section Black Belt	60, 70, 55, 60 (-)	Extensive green roofs were investigated at two substrate depths and two deck slopes were investigated. The succulent vegetation	Anders and Walker (2011)
	Region average retained 67%			

The research sites in the Midwest (Table 7) were located in East Lansing, Michigan and Southfield, Michigan. Both research sites fall within the NRCS rainfall distribution Type II. The precipitation occurred as snowfall and rainfall. The average volume retention for the region was seventy-four percent. The research at Michigan State University was one of the first in North America to study effects of slope and stormwater retention. Flat roofs (2% slope) retained more precipitation (85.6% retained) than roofs sloped at 25% (76.4% retained). The stormwater curve number for flat roofs was 84 and for 25% sloped roofs was 90, both better than the conventional control roof curve number of 98.

Table 7 Average stormwater retention and flow rate reduction from extensive green roofs in the Midwest geographic region

Research Site Location	Eco-region of Research Site	Ave. retention and (flow rate) % reduction	Major Points Discussed	Study
East Lansing, MI	S. Central Great Lakes	68-74 (-)	Multiple slopes and depths studies on shallow extensive succulent green roofs. Shallow substrates produced more runoff. Green roofs continued draining 3 hours after rain event compared to gravel roof. Sloped vegetated roofs retained much more water than flat conventional gravel ballasted roofs.	Rowe (2003)
East Lansing, MI	S. Central Great Lakes	75-85 (-)	Plants established 3 years prior to data collection. Plant maturity increased retention from 17% to 67%. Curve numbers: 2% slope (84), 7% slope (87), 15% (89), and 25% slope (90). Slope had a negative effect on runoff retention curve numbers.	Getter et al. (2007)
Southfield, MI	Lake Whittlesey Glaciolacustrine Plain	68 (84)	The retention observed for the green roof was 68.24% which was compared with two conventional roofs. A bituminous membrane roof retained 10.44%, and a rock ballasted roof retained 48.55%. The green roof also showed a reduction of peak flows with an average of 84%.	Carpenter (2009)
	Region average retained 74%			

4.3 Other findings

Several important findings were shared across geographic regions. In most investigations, small rainstorm events (less than 1.5 cm) resulted in very little to no runoff from green roofs if the roofs were not saturated prior to the rain event (T. L. Carter & Rasmussen, 2006; DeNardo, Jarrett, Manbeck, Beattie, & Berghage, 2003; Dvorak, Volder, & Aitkenhead-Peterson, 2011; Glass & Johnson, 2008; Hutchinson et al., 2003; Johnston, McCreary, & Nelms, 2004; Kurtz, 2008; K. Liu & Baskaran, 2003; K. Liu & Minor, 2005; MacMillan, 2004; Charlie Miller, 1998; Monterusso et al., 2004; Moran & Smith, 2005; Rowe et al., 2003; Van Seters, Rocha, & MacMillan, 2007). Another shared finding was the relationship between saturated growth media and a reduced capacity to retain runoff (Miller 1998; Liu and Baskaran 2003; Rowe, Rugh et al. 2003; MacMillan 2004; Monterusso, Rowe et al. 2004; Moran, Hunt et al. 2004; Liu and Minor 2005; Getter, Rowe et al. 2007; Van Seters, Rocha et al. 2007; Glass and Johnson 2008; Dvorak et al. 2011), although one paper from the Pacific Northwest reported that fairly consistent retention and runoff rates were maintained throughout storms when media was previously saturated (Hutchinson, Abrams et al. 2003), and another reported no correlation between rainfall retained and the time between rain events (DeNardo, Jarrett et al. 2003). Although green roofs were very effective in absorbing small and even some medium rainfall events, depending upon the storage capacity of the green roof substrate, most were not able to retain all of the precipitation from large rainfall events. In line with these findings are observations that research plots that were regularly irrigated (without moisture sensors) were somewhat hindered in their capacity to retain stormwater (MacMillan 2004), but if rainwater harvesting with cisterns was included as part of the system, annual retention rates greatly increased as one investigation found that no water left the cistern for the entire year (Wanielista et al., 2008).

Similarities and differences were observed resulting from seasonal characteristics across regions. Spring and summer rain events were more likely to result in greater proportions of retained precipitation than rain events during the fall or winter at many investigation sites (Rowe, Rugh et al. 2003; Johnston, McCreary et al. 2004; MacMillan 2004; Liu and Minor 2005; Carter and Rasmussen 2006; Van Seters, Rocha et al. 2007; Kurtz 2008), but during some investigation periods, heavy rain fell only during the summer and the green roof became saturated and therefore less effective but still more effective than controls (Liu and Baskaran 2003). A study in the Pacific Northwest compared results from two years that had similar total rainfall amounts but different distribution patterns and found different runoff rates due in part to the pattern or distribution of rainfall (Hutchinson, Abrams et al. 2003).

A few investigations looked at the contribution of growth media to the retention and evaporation of stormwater (Rowe, Rugh et al. 2003; VanWoert, Rowe et al. 2005). Sedum-vegetated plots (2.5 cm to 6 cm) were compared with non-vegetated plots and were found to be about 10% more effective than media-only plots during rain events, but the sedum-vegetated green roof plots were still less than 1 year old and had not yet reached maturity.

Roof slope was another variable investigated at a few sites, with mixed results. A newly planted study found no significant difference among slopes of 2%, 5%, and 15% (Rowe, Rugh et al. 2003; VanWoert, Rowe et al. 2005) but later found those same trail plots at a more mature condition to exhibit differences (VanWoert, Rowe et al. 2005). In later investigations, an additional slope category of 25% was added and it was found that slopes of 25% were effective at retaining runoff up to 77%, whereas green roofs with slopes of less than 2% had a rate of 85.6% (Getter, Rowe et al. 2007).

Other mixed results include investigations of the effect of the thickness of growth media. Some investigations found little difference between very shallow (2.5 cm) and shallow (4 cm) green roofs (Rowe, Rugh et al. 2003; VanWoert, Rowe et al. 2005) and between shallow (5 cm) and thicker (10 cm) green roofs (Moran, Hunt et al. 2004), whereas other investigations found differences between them (Getter, Rowe et al. 2007). One study that made use of rainwater harvesting with cisterns found that the combination of using a green roof and a cistern to recycle water and irrigate the green roof retained 80% of annual runoff in one study (Wanielista and Hardin 2006) and 100% of rainwater that fell on the roof for that year (Wanielista, Hardin et al. 2008) in another study.

Modeling was used to estimate the effectiveness of green roofs at the watershed scale in urban environments (Miller 1998; Johnston, McCreary et al. 2004; (T. Carter & Jackson, 2007); Jarrett and Berghage 2008; (Taylor, 2008)). Stormwater runoff coefficients (CN) were investigated and determined so to represent the porosity of green roofs. One investigation used 10-cm-deep green roof data and found that the green roofs averaged a CN of 86 (Carter and Rasmussen 2006) and in a different study, investigators used 2.5-cm and 4-cm-deep green roofs and found CN values varied from 84 to 90 (Getter, Rowe et al. 2007).

5 DISCUSSION

The findings across geographic regions indicates that green roofs in North America have similar retention rates (52%-74%) (Table 1) to those in Europe (40%-70%) (Klaas, 2012); however, there are times and conditions where the green roofs were not very effective. The size of the rainfall event, the moisture in the substrate prior to the rainfall event, this thickness of the substrate and the time of the year appear to play a large role in the effectiveness of the green roofs. Also design of the green roof system demonstrated large differences in one study; however, the data set was limited (Simmons et al., 2008).

One of the most influential factors found in nearly every study was the size of the rainfall event. This is not surprising since small storms (< 1 cm) typically generate little runoff, even on rooftops. Large storms (> 2.5 cm) were consistently in the category of least volume retained. There are mixed results in the moderate storms across regions, as the investigations varied greatly in length of study, time or season of the research, and type of vegetation. More detail from the investigation sites is needed as not all papers reported hydrographs or tables with rainfall retained for each event.

Another influential factor in the capacity of the green roofs to retain precipitation was the amount of moisture in the substrate prior to a rain event. It was reported in several papers that the more moisture present in the substrate prior to a rain event, the less effective the green roof was in retaining precipitation. Several papers reported that if the green roof had a few days to dry out, then its retention capacity was restored. One paper reported that regular irrigation hindered the capacity of the green roof to retain rainfall.

One investigation reported that if succulent green roofs with shallow substrates are to be irrigated in the Midwest, then irrigation only once every two to four weeks may be necessary for plant survival. The rate of irrigation for succulent green roofs appears to be minimal to keep vegetation healthy in some of the studies. This suggests that plant selection and maintenance are critical to the performance of the green roofs. Research on plant forms also suggests that mixed designs with succulents, forbs and graminods may be best for retention of precipitation year-round for some regions (J. Lundholm, MacIvor, MacDougall, & Ranalli, 2010).

The thickness of the substrate appears to make some difference in performance. One study found that very shallow (2.5 cm to 4 cm) deep substrates provide some benefit, but when green roofs are at least 10 cm deep, then their effectiveness greatly improves. Very few, intensive green roofs with deep substrates (>20 cm) have been investigated. The few that have been studied demonstrate that they can retain most of the rainfall (Berndtsson, Bengtsson, & Jinno, 2009).

The effect of season was reported in some but not all papers. Where season was reported the results are mixed. In Toronto, the summers of the periods of investigation were wetter than normal. The substrates were often saturated and the green roofs were reduced in capacity to retain water. The green roofs were also irrigated and thus the capacity to retain water was further reduced. Conversely, winters in the lower elevations of the Pacific Northwest tend to be cool but not frigid with ample precipitation; however, the summers are typically dry. In the Midwest and Mid-Atlantic regions, winters can be frigid with extended periods of frigid air temperatures where plants are dormant. Precipitation can be persistent during the summer in these regions as well, with days or weeks with continuous rainfall. The Southcentral U.S. studies demonstrated that the green roofs can be effective during the growing season as summers are dry and hot. The substrates tend to dry out quickly if irrigation is reduced or not present.

These findings are important for landscape architects involved with research, teaching, private practice, or service in municipal or governmental agencies because it appears from the research that there are differences in performance across regions. One should be aware of the influence of rainfall patterns, plant selection and substrate design. One design characteristic only reported in a few papers was the compliance of substrates with the universal German FLL Green Roof guidelines. North America has few guidelines for design of green roofs and more research is needed in North America to better understand the role of substrate and drainage layer design in retention (Dvorak, 2011). Hutchinson et. al. (2003) reported that one of the substrates was very porous and did not effectively retain precipitation. The design characteristics of the substrate in that research were not reported. Consistency in reporting substrates is needed to better understand what the findings mean. With greater reporting of green roof substrates, design details, and drainage designs, the more applicable the findings are and can be used to compare with similar studies.

In terms of stormwater retention, the question of whether to irrigate or not seems to be less important than how much water should be applied. It seems that if a priority of the green roof is to retain stormwater, then irrigation must be minimized or not used during times when consistent rainfalls typically occur. Plant materials must be selected to survive from year to year; however, there may be gradations of good designs from succulent dominated green roofs to meadow-like green roofs or mixed designs. With so few investigations to represent the many ecological regions across North America, we may not have an accurate understanding of how to design green roofs for specific eco-regions.

Regarding the distribution of research across disciplines, there were only a few landscape architects involved with publishing green roof stormwater research. This area of work needs more participation by landscape architects so that landscape architects can better understand and teach about green roofs for low impact designs and watershed planning locally. With the advent of the many landscape metric systems, green roofs are often used but local research many be need to maximize their ecosystem services. Education, research and design characteristics of green roofs are in the domain of landscape architecture, and cross disciplinary collaborations are encouraged to expand the knowledge base within landscape architecture.

Regarding limitations of the statistical analysis, the number of investigations ranged from two to seven for six regions. The limited data set did not allow for an in-depth cross examination analysis. With future publications throughout the regions, updates to statistical analysis and reevaluation of regions could be made.

6 CONCLUSIONS

From the review of the thirty-two investigations in North America, the green roofs retained from fifty-two to seventy-four percent of precipitation events across six geographic regions. There are geographic regions, however, with large areas of urban development that were not represented (New York City, Washington D.C., Houston, Miami, Los Angeles), and there were only a few papers that reported detail regarding the substrates and plants used on the study. More research is needed to capture performance in the Southeastern and Southcentral U.S., Mid-Atlantic and regions. There was no research in the southwestern U.S and west coast. Also, because of the low number of papers, more research is needed regarding seasonal variations and flow reductions to more accurately understand how green roofs perform. Generally, Landscape architects were not represented in the pool of research investigations, but could become involved to make important contributions to research and understand how green roofs that landscape architects design perform. Bill Thompson was right that landscape architects in professional practice would make use of green roofs in a big way in the first decade of the twenty-first century. However, thus far, Landscape architects have not participated with green roof stormwater research, but should become involved to help learn about the technology and teach a new generation of landscape architects how green roofs can be designed to effectively manage ecosystem services.

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