JOURNAL
OF LIVING ARCHITECTURE
A GREEN ROOFS FOR HEALTHY CITIES PUBLICATION

Volume 7 Number 1 Pages 27-64 2020

Green Roof Research in North America: A Recent History and Future Strategies

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ABSTRACT

Since the year 2000, green roof and living architecture research has progressed significantly in North America. For future growth in the implementation of living architecture, there is still a great need for additional and expanded research on green roofs and as yet undefined innovative green infrastructure. This paper provides an overview of priority topics that have been critical to past success in green roofs, and those that are promising but need future investment, including urban heat island (UHI), energy savings, stormwater (quantity and quality), substrates, carbon budgets, plants, biodiversity, ecomimicry, biodispersal, long-term dynamics, urban food production, synergy with solar panels and financing green solutions.

Key words: Living Architecture, Green Roof, Green Infrastructure, UHI, Substrate, Stormwater, Carbon Budgets, Biodiversity, Ecomimicry

INTRODUCTION

In the first two decades of the twenty first century, research has progressed in North America and beyond, developing a vital body of literature that is helping define the global understanding of the emerging field of living architecture. Living architecture includes green roofs, green walls, and related green infrastructure systems. Green roof and other living architecture research increasingly requires a highly multidisciplinary approach, including fields such as biology, ecology, engineering, horticulture, climatology, architecture, and landscape architecture.

In an effort to aid North American collaborative efforts, the professional trade organization Green Roofs for Healthy Cities (GRHC) and the Green Infrastructure Foundation (GIF) solicited academic institutions to develop Regional Academic Centers of Excellence (RACE) in Living Architecture. At the 2018 CitiesAlive! Conference in New York, four centers were announced: Colorado Living Architecture (CLA), Greater Ohio Living Architecture Center (GOLA), Southern Illinois University Edwardsville (LARCE), and the Stevens Institute of Technology. Since their initiation, the RACE in Living Architecture academics have coalesced to begin addressing the challenges and gaps that currently exist in living architecture research.

To provide context for a discussion of how to move forward, the RACE in Living Architecture members wrote this manuscript as a major step towards identifying existing research knowledge around the urgent research needs identified by a 2017 survey conducted by GRHC. This paper provides an overview of priority topics that have been critical to past successes with green roofs and green infrastructure, and those that are promising but need future investment. These topics include urban heat island (UHI), energy savings, stormwater (quantity and quality), substrates, carbon budgets, plants, biodiversity, ecomimicry, biodispersal, long-term dynamics, urban food production, synergy with solar panels and financing green solutions.

Faculty, students, and collaborators in the RACE conduct vital research that supports the green roof industry. We advocate for additional research funding from local, regional, federal, and international organizations (including government agencies, trade organizations, and the green roof industry) to support these current and emerging green roof issues. These collaborative, concerted research efforts will continue to foster North American growth and development of green roof knowledge for a more sustainable future for the industry and for our species.

Current Research and Urgent Areas of Need by the GRHC Research Committee

In the spring of 2017, a survey of the GRHC Research Committee Members was conducted to determine the research activity and need in green roofs. At the time, there were 46 members of the Research Committee representing 33 academic and public institutions. The majority of the members were from academic programs in biology, ecology, horticulture, and landscape architecture. The response rate was 34%. The survey requested the following information:

- respondent's name, institution, location
- length of time in the area of research
- funding sources and amounts
- areas of current research in four categories:
    - benefits
    - innovation and technology
    - planning, design, and maintenance
    - policy and incentives
- urgent areas of need for research in the above categories.

Figure 1 shows that most research has focused on the benefits of green roofs. The researchers' input for "urgent areas of need for research" is reviewed below.

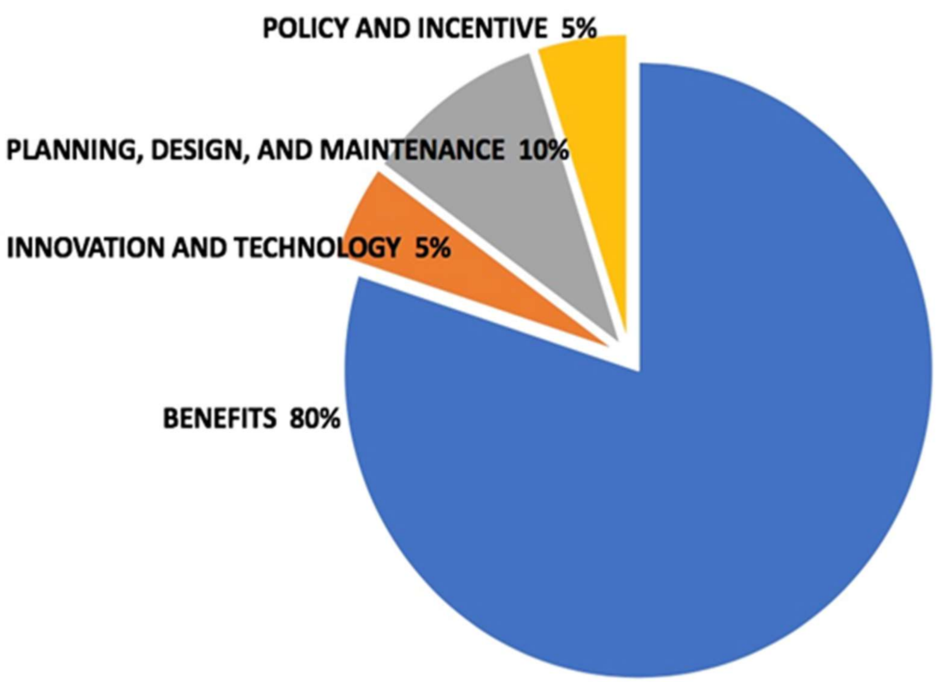

Figure 1 Survey respondents indicate that current research is overwhelmingly associated with the benefits of green roofs.

Benefits

Most survey respondents indicated that research in stormwater mitigation (quality and quantity) is urgent, which is also the most frequently listed topic of current research. It is possible that the frequency with which stormwater is mentioned as both a current research topic and an urgent research topic is directly related to the availability of funding sources for this "hot" topic.

The more typical research topics associated with the benefits of green roofs, such as stormwater mitigation, energy conservation, the development of biodiversity, and improving air quality, were mentioned as "urgent areas of need for research." However, additional broad and specific urgent research needs around benefits were listed that are not currently studied or not studied in proportion to the need for knowledge in these areas:

- return on investment (ROI) based on true costs
- life cycle costs
- social and cultural implications of green roof
- carbon / nitrogen / other elemental sequestration and offsets
- nutrient limitations of plants
- low phosphorus substrate options and phosphorus retention
- long-term studies *in situ*
- research methodology and consequences.

Innovation and Technology

It is likely that most research for innovation and technology is conducted within the proprietary confines of industry, or "off the grid" in entrepreneurial environments that are not necessarily associated with GRHC or its Research Committee.

Few respondents indicated any research activity in topics related to innovation and technology other than alternative substrate and native plant mortality, but a few were responsive with ideas related to urgent areas of need for research:

- figure out how to make retrofits feasible (design, engineering, economics, etc.)
- innovation to reduce weight constraints
- alternative plant palettes/nutrient requirements
- alternative sustainable materials and methods, particularly substrates
- integration with LEED / SITES® / Living Building Challenge's Red List
- collaborative, ecoregional approaches that foreground sustainability, including
    - ecosystem connectivity and wildlife corridors
    - regional sourcing of materials
    - sky to ground systems for water and energy
    - *in situ* research stations
    - strategies for greywater and blackwater.

Planning, Design, Maintenance, and Education

Very few members of the GRHC Research Committee are conducting research in topics of this realm, and few suggestions of "urgent areas of need for research" were offered. The following topics were gleaned from the Design Track of GRHC conferences and symposia as indicators of topics selected for their timeliness and need for shared knowledge and from this author's recognition of voids in the training associated with green roofs:

- regionalism
- typology and taxonomy
- pedagogy
- theory
- post-occupancy evaluation methodology
- unique design strategies/alternatives to turnkey systems
- marketing strategies
- performance of modular and tray systems vs. loose-laid / built-up systems
- design for a diversity of users and uses
- design for research.

Policy and Incentives
The respondents - members of the GRHC Research Committee - are connected to topics in policy or incentives directly or indirectly as their research serves to substantiate the need for and development of both. GRHC's staff and volunteers are the most proactive contributors to the body of knowledge in this realm. As North American policies and incentive programs spread and experience is accumulated, it will be important to evaluate the performance of various policies and incentive programs (carrot vs. stick, for example) and the dollar-for-dollar value of incentive programs. This type of research will necessitate an expansion of the green roof research community in new areas of expertise, which are required to study the following "urgent areas of need for research" identified by respondents:

- policy to favor retrofits over new construction in support of sustainability
- building code, land use regulations
- reducing the costs of materials, installation, and maintenance
- wind and fire standards for varied profiles
- a systematic review of standards, codes, policies, incentives followed by systematic awareness and outreach campaign
- impact studies for quality of life/social implications
- investigation of tipping points for the adoption of policy/incentive; interaction of social factors and economics and other influences
- protective legislation for biodiverse or historically significant landscapes over structure
- comparative studies of green roofs vs. blue roofs vs. cool roofs
- the interface of solar panels with green roofs (benefit or detriment, and how much?)
- monitoring the impacts of policy and incentives.

Summaries
The summaries of the current state of research presented below align with the proportions of the survey results (Figure 1), with the majority addressing research related to benefits (UHI, energy, solar panels, stormwater management, carbon budgets, biodiversity/ecomimicry/ biodispersal, and urban food production). Three summaries – substrates, plants, and long term dynamics – would be classified as topics related to planning, design, and maintenance. The summary on financing nature-based solutions (NSB) is related to policy and incentives. On

the surface, it would seem that the category regarding innovation and technology has not been addressed, but in fact, each of the summaries describes new approaches and new interpretations that directly impact innovation and technology as well as providing new foundations for policies and incentives. All of the summaries presented here are connected to the topics identified as "urgent areas of need" in research, and these and the other topics listed in the survey results make transparent the need for funding to support research in all categories that will further the successful implementation of green roofs.

LITERATURE REVIEW

Urban Heat Island Effects

Urbanization, the gradual shift of people moving from rural to urban areas, combined with population growth worldwide, contributes to an increase in impervious surface area and elevated temperatures in cities versus outlying rural surroundings (Ritchie and Roser 2018). This difference in temperature is referred to as the urban heat island (UHI) and occurs because dry and impermeable buildings, roads, large parking lots, and other hard surfaces replace the once permeable, moist, and vegetated surfaces (Imhoff et al. 2011).

Covering hard city surfaces with vegetation, such as green roofs, is one of the main strategies for reducing UHI (Gartland 2012). The benefits of using green roofs for UHI mitigation has been well documented over the past decade (Alexandri and Jones 2008; Bass et al. 2003; Bowler et al. 2010; Gaffin et al. 2008; Köhler et al. 2003; Lundholm et al. 2010; Razzaghmanesh et al. 2016; Rosenzweig et al. 2006; Scherba et al. 2011; Susca et al. 2011; Takebayashi and Moriyama 2007).

Despite much emphasis on observing and documenting UHI in cities worldwide over the past decades, Stewart (2011) points to gaps and lack of precision in their scientific critique of methodology and systematic review of UHI literature from the 1950's - 2007. They concluded that only half of about 190 qualifying UHI studies passed the test. This is likely due to the difficulty and complexity involved in measuring and documenting UHI effects and aspects. Recommendations given by Stewart (2011) for improving methodological quality in UHI studies include: reduction of spatial and temporal resolution in data sets; following standardized guidelines for site reporting (Oke 2004) and classification systems (Stewart and Oke 2009); disclosing limitations of data; using UHI terminology with precision and discretion; scrutinizing initial UHI findings, and not accepting initial findings at face values.

Additionally, over the last decade, there have been studies with a focus on measuring UHI through modeling (Sailor and Dietsch 2007; Wilby 2008), economic analyses of energy savings and environmental benefits in green roof mitigation of UHI (Akbari and Konopacki 2005; Clark et al. 2008; Rosenfeld et al. 1995), green roofs contribute to the reduction of UHI through reduction of heat flux (Getter et al. 2011; Tabares and Srebric 2009), and mitigation of UHI through green roofs ability to cool in combination with solar panels (Ogali and Sailor 2016; Scherba et al. 2011).

Although the UHI and associated green roof cooling benefits have been well documented over the past decades, there is still a lack of studies that show how optimizing the health and diversity of ecosystems increase productivity and resilience (Cardinale et al. 2012), and how the increased health of these vegetated systems help maximize overall evapotranspiration and cooling and thereby increase the mitigation of the UHI.

Urban landscape conditions across North America are vastly different, and there is a need for studies and research that can help establish BMP's and guidelines for green roof design, installation, and maintenance site-specific to local ecoregions (Snodgrass and McIntyre 2010; Tolderlund 2010). That, in turn, will help maximize the mitigation of UHI. As also pointed out by Nash et al. (2019), very little research has been done to study how the ecology and ecological process of various types of green roofs contributes to, and maximize, the mitigation of UHI. This is likely due to the complexity and cost of such studies.

Great potential for future UHI studies includes determining what spatial configuration of building and neighborhood designs best help maximize green roof contributions to the mitigation of UHI (Carter and Butler 2008; Cheung 2011), especially if scaled up and tested as part of connecting green roof systems with surrounding landscape parks and corridors, to increase ecosystem services in urban areas (Carter and Butler 2008; Taha et al. 1999). Additionally, evaluating individual vegetation species ability to cool, varying combinations of vegetation, level of adaptation to local conditions; types of substrate, and varying substrate depths, for green roof systems, can also contribute to the overall knowledge of systems-based mitigation of UHI.

Energy Saving Aspects

In recent years, the effect of building insulation on heating and air-conditioning energy consumption has become more significant as energy costs have increased. In order to combat rising costs, insulation technologies have been improving. Most of the insulation materials available in the market are synthetic. Green roof systems, however, are live insulation systems with multiple benefits in addition to reducing heating and cooling energy costs, such as reducing stormwater runoff, filtering pollutants and carbon dioxide out of the air, decreasing the UHI effect in cities, and increasing the lifespan of roofing materials.

Numerous studies on the thermal benefits and energy savings potential of green roofs have been published. Sailor (2008) focused on the design process of green roofs by using a program developed by the U.S. Department of Energy. For energy budgeting, FASST (fast all season soil strength model), developed by Frankenstein and Koenig (2004) was employed. The green roof simulation module developed in Sailor's study was implemented in the EnergyPlus building energy simulation program. The model enables quantitative analysis of potential energy savings from green roofs. Niachou et al. (2001) studied the thermal performance of green roofs for different building scenarios. The study showed that as the building overall insulation is enhanced, the percent contribution of green roofs to insulation declined.

Peters et al. (2013) investigated the energy savings analysis of a campus building in the southeastern U.S. with a green roof housing *Sedum* spp. Lower temperature readings were recorded, resulting in reduced HVAC costs. Mukherjee et al. (2013) performed a simulation analysis to quantify cooling loads on a sample building in three different cities; Chicago, Los Angeles, and Phoenix. The study examined the effect of LAI and soil depth as well. The results revealed that the cooling loads were reduced for all three simulations in a range of 18-21%. Berardi (2016) looked at the microclimate benefits of green roofs that relate to the UHI effect. A noticeable decrease in the surrounding ambient temperature was observed around and atop buildings where green roofs were placed. Celik et al. (2019) conducted a comparative energy savings analysis on green roofs and shingle roofs at varied roof slopes in the Midwest. The comparative energy study revealed an average cooling load reduction of 50% through the roofs covered with vegetation.

Almost all studies published on thermal benefits and energy savings potential of green roofs indicate that the thermal performance increases with increasing substrate depth, plant coverage, and leaf area index. The porosity of the substrate also plays a significant role due to its effect on evapotranspiration. As the porosity of the substrate increases, so does the evaporative cooling potential of the green roof. In past years, thermal studies have been focusing more on these parameters as the accuracy of energy savings analysis vastly relies on these parameters. Energy savings analysis of green roofs and green infrastructure could benefit from further research on the interaction of plant roots and substrate and its impact on evapotranspiration and evaporative cooling. Future work on synergistic green roof-solar panel applications possesses the potential to contribute significantly to the literature in terms of the mutual benefits to thermal impacts and plant growth.

Stormwater Retention and Quality

Stormwater Retention

One of the most critical design principles of green roof systems includes providing sufficient substrate capacity to support plant growth. Components/materials blended into the substrate mix determine the nutrient and moisture-holding capacity of a specifically designed and engineered substrate. Green roof installations will ultimately fail if the substrate does not provide what the specified vegetation requires for survival and growth. While most substrate is designed to provide sufficient moisture-holding capacity to support plant survival and growth, an additional benefit is the retention of a certain proportion of the stormwater (precipitation) that is deposited on a green roof system. Thus, whether a system is designed to be intensive or extensive or is specified as a built-in-place or modular system, one of the primary environmental benefits, or ecosystem services, provided by a green roof is stormwater retention with a secondary benefit of potential improvement of the downstream runoff water quality.

While the principle of the addition of a green roof to an urban landscape is to replace or restore the natural ecosystem and ecosystem services, green roof systems by design are often disconnected from ground infiltration (and groundwater recharge). Thus, below a minimum threshold precipitation event, green roofs may function as a zero-discharge system (Eger et al. 2017). In other words, following a low to moderate precipitation event, no precipitation that falls on the green roof surface typically runs off nor does it discharge into the groundwater. Therefore, establishing an appropriately designed green roof system in a climate where there is a high frequency of small, less intensive rainfall and with a relatively high evapotranspiration potential will generally lead to significant stormwater retention (Carpenter and Kaluvakolanu 2011; Elliott et al. 2016; Sims et al. 2016; Speak et al. 2013). If a green roof system is located in a climate with frequent intense precipitation events, the proportion of stormwater retained will be reduced even if the climate has a relatively high evapotranspiration potential. System design for anticipated precipitation events is critical to maximizing green roof stormwater retention (Stovin 2010).

However, no matter the design (e.g., intensive or extensive, built-in-place or modular, etc.), every green roof application has a maximum moisture retention limit – every system reaches saturation at some point. In fact, during particularly large or intense precipitation events or during extended periods of frequent low volume precipitation events, green roof systems will retain and evaporate proportionally less water (Eger et al. 2017). The timing of a previous precipitation event will impact the green roof system moisture-holding capacity. Even a small precipitation event on the heels of another precipitation event that saturated the system will result in stormwater runoff. An ideal system will begin to evapotranspire moisture from the green roof system as soon as a precipitation event is over, both through evaporation from the substrate and transpiration by the vegetation (Liu et al. 2019b; Richter et al. 2009).

System features including the porosity of the substrate, substrate composition, and substrate depth have been found to significantly influence evapotranspiration as well as the choice of the plant palette and the transpirational characteristics of the specific plants in the system (Farrell et al. 2013; Morgan et al. 2013; Nagase and Dunnett 2011; Richter et al. 2009; Szota et al. 2017; Wolf and Lundholm 2008). In many research experiments evaluating the stormwater retention of green roof systems, unplanted substrate systems have been shown to have significant average stormwater retention values (Morgan et al. 2013; Zhang et al. 2019) even though these unplanted systems do not provide additional ecosystem services as would be provided in living systems (e.g., biodiversity benefits).

Frequently overlooked when considering green infrastructure to improve the urban environment, the residential roof surface area (often sloped) can be as much as five times greater than the commercial roof surface area in an urban setting (Carey 2004). However, roofs with steep slopes retain less stormwater than those with less slope and the same substrate depth (Murphy et al. 2018; VanWoert et al. 2005a).

Recent evidence from scale-based models and experiments indicates that the contributing factors to stormwater retention by green roof systems in order of influence are as follows: substrate material > substrate depth > slope > vegetation (Liu et al. 2019b). It is exceptionally clear that precise system design, taking into account all of these factors and the local climate, is key for optimal green roof stormwater retention performance.

Runoff Quality

Much like the requirement for precise system design for maximizing stormwater runoff retention by green roof systems, green roofs and walls should be constructed to match runoff water quality expectations to mitigate any downstream pollution risk (Liu et al. 2019c). Just like stormwater runoff quantity, runoff quality of green roof systems is dependent upon substrate material, substrate depth, and vegetation composition and can vary greatly. In an experimental stormwater retention system evaluation of multiple green roof models over an 18-month period with measurements at multiple precipitation events, the pH of runoff ranged from 5.3 to 7.7 and was independent of substrate depth, system design, and whether planted or unplanted (Woods 2011 – from Morgan et al. 2013). The pH of runoff was also similar between non-green roof systems (EPDM roof membrane surfaces and unplanted systems composed of substrate only) and green roof systems. In the same study, the nitrate in runoff from the model systems ranged from 3.0 ppm to 70.3 ppm over a 15-month period while the nitrate in runoff from models comprising a traditional roof system never went above 4.0 ppm.

Most studies have focused on nutrients in green roof runoff (Hathaway et al. 2007; Monterusso et al. 2004; Moran et al. 2004; VanWoert et al. 2005b; Wu et al. 1998). Yet, the total suspended solids (TSS) and the turbidity of runoff water are regulated (USEPA 2003a,b). In an experimental pot-study analysis of planted green roof systems, the TSS and the turbidity of runoff water was elevated in first-flush runoff and decreased over time (Morgan et al. 2011). Most particles that resulted in TSS and turbidity were those that "washed" from the substrate, suggesting that efforts to reduce the "dust" before placing the substrate in the system would help to resolve this issue. This practice will be especially important in areas with stringent water quality regulations. The addition of, or improvement of, a filter layer within the green roof system may also go a long way toward reducing the suspended solids in green roof stormwater runoff (Liu et al. 2019c).

Traditional roof surfaces have been shown to contribute contaminants and nutrients to stormwater runoff (Alsup et al. 2013; Mason et al. 1999) due to dry and wet deposition that is washed off the roof during a precipitation event. Model green roof systems of different compositions or depth were shown not to be sources of metal contaminants in stormwater runoff (Alsup et al. 2013). However, it should be noted while the green roof systems evaluated did not behave as sources for the metals examined, the systems also did not behave as sinks or contribute to the removal of metals in the wet deposition input into the systems (Alsup et al. 2013). Water quality of runoff from a green roof system also varies depending upon other inputs into the system, such as fertilizer and organic amendments.

The variability of results in the few studies related to pollutants in runoff from green roof systems indicates that the design of green roof systems must consider the individual components of the system as well as any inputs to the system in order to minimize any downstream water quality impacts (Retzlaff et al. 2008). Tradeoffs may be needed to obtain a balance between retention and quality impacts.

Even though much has been done to demonstrate the value and performance of green roof systems to retain, delay, and even filter stormwater, much more research evaluation still remains to demonstrate long-term performance and system viability. None of the research studies cited in this review evaluated stormwater retention of green roof systems beyond 2.5 years, yet there are green roof installations in Europe that are 100+ years old and installations in North America that are approaching 50+ years old. Many research questions still remain as we work to mitigate the stormwater issue in the urban environment with green roofs. What combination of substrate and plant material provides the best options for stormwater retention at a given location? Can we develop a prescription tool that would permit a designer and installer to pick/identify key local components for systems whose objective is stormwater retention? Does the amount of stormwater retention by a green roof change as the system ages? As components of the system change (e.g., substrate breakdown, material aging, and plant maturation), does the presence or absence of contaminants in the runoff from these systems change?

Substrates

The relative success of most green roof plants depends primarily on the substrate. The depth, composition, water holding capacity, and chemical and physical characteristics of the substrate must be aligned with the climate, the plant palette, and the desired benefits of the green roof system. As both Ampim et al. (2010) and Olszewski and Young (2011) point out, the information and research results related to green roof substrates is still quite limited. Of course, that may have to do with the fact that many green roof manufacturers have their own proprietary blends.

The primary component of most North American green roofs is an expanded aggregate, most often expanded shale, clay, and slate (ESCS) (Ampim et al. 2010; Friedrich 2005). ESCS are produced by expanding in kilns or by pelletizing or sintering the raw material (Friedrich 2005). In an experiment in Michigan, as expanded slate increased in percentage (60-100%), *Sedum* spp. growth decreased; however, by the end of the two-year study, all levels of expanded slate had full coverage (Rowe et al. 2006). Olszewski and Young (2011) found that *Sedum floriferum* did not thrive in any level of expanded clay, although that could be due to the fact that the substrate was only 2 cm deep and became dry as soon as one day after watering.

Substrate depth is another important factor in the relative success of green roof systems, primarily due to the fact that deeper substrates may detain more water. Not only did water availability in the shallow substrate of the Olszewki and Young (2011) study influence plant success, but VanWoert et al. (2005b) found a similar result in 2 cm of substrate. However, it is worth noting that deeper substrates support larger plant canopies and therefore evapotranspiration rates (and subsequent irrigation demands) are higher (VanWoert et al. 2005b).

Specific components or amendments to green roof substrates have been evaluated in the green roof literature. Water quality and water detention improve when 7% biochar is included in green roof substrate (Beck et al. 2011). Adding nitrogen-charged zeolite, which has an incredibly high cation exchange capacity (CEC) to green roof substrate improved plant growth of *Sedum* spp., depending on species, in the first year or the second year of growth (Bousselot et al. 2012). In an evaluation of green roof substrates in southern Illinois with arkalyte, hadite, pumice, and lava rock, the *Sedum* spp. performed the best in the pumice substrate, although it was bit significantly different from the hadite treatment (Gibbs et al. 2006).

Additionally, there is a lot of interest in alternatives or additives to traditional green roof substrates such as recycled materials or native soils. Eksi and Rowe (2016) investigated the use of recycled crushed porcelain and foamed glass as components of green roof substrates. While the study plants did best in the traditional green roof substrate, these recycled materials show promise as components of green roof substrates and can reduce the amount of embodied energy required to formulate green roof substrates (Eksi and Rowe 2016). Using native soils as amendments to green roof substrates can help green roofers attempt to recreate habitat for the microorganisms, flora, and fauna of an ecosystem and therefore possibly find a home on a green roof (Best et al. 2015).

Every green roof substrate component, whether inorganic or organic, has both advantages and disadvantages (See Tables 3 and 4 in Ampim et al. 2010). It is the most ideal to formulate the green roof substrate based on the needs of the project. In terms of green roof substrate research, little has been published in the peer-reviewed literature, leaving the field open for significant leaps in innovation.

Carbon Budgets

There are three main mechanisms by which green roofs can impact land-atmosphere carbon (C) exchange: (1) The direct function of the green roof vegetation and substrate as sinks or sources for C during the lifespan of the green roof ecosystem; (2) through the C cost of the energy required for construction (embodied energy); and (3) through green roof insulative properties and impact on heating and cooling energy demand for the building and region (e.g., Kotsiris et al. 2019; Rowe 2011; Sailor and Bass 2014). To quantify the total C impact of a green roof system, a life-cycle analysis considering all these aspects should be undertaken (Engström et al. 2018; Kavehei et al. 2018). This review focuses primarily on the first mechanism, (e.g. potential for C sequestration by green roof ecosystems) and focuses on extensive (*Sedum* spp.) green roofs where most of the research has taken place.

Since the pioneering Oberndorfer et al. (2007) paper proposing the study of green roofs as ecosystems, a number of advances have been made in research on C cycling and C budgets in green roof systems, with North American researchers playing an important role (Li and Babcock 2014; Starry 2016). Like any vegetated space, green roof systems have the potential for biomass and soil (substrate) accumulation that can represent a C sink, if C inputs to the roof exceed exports over the lifespan of the ecosystem. For green roof systems, the major fluxes in and out of the ecosystem are presumably atmospheric CO_2 in (associated with primary production), atmospheric CO_2 out (associated with autotrophic and heterotrophic respiration), and hydrologic runoff losses of dissolved organic carbon (DOC) from the leaching of soil organic matter (Buffam and Mitchell, 2015).

There is still relatively little known about atmospheric CO_2 exchange in green roof ecosystems – but knowledge is growing. Gaumont-Guay and Halsall (2013) for instance carried out year-long measurements of CO_2 exchange for a newly-established extensive green roof in British Columbia, Canada. Based on these measurements, this particular roof was near steady-state with respect to atmospheric CO_2 exchange (e.g. not serving as either a strong sink or source). More recently, Heusinger and Weber (2017) measured net ecosystem exchange of CO_2 of a green roof in Berlin, Germany, and found the roof to be a net sink for CO_2, at a rate of 85 g C m^{-2} yr^{-1}. For context, growing temperate forests typically have net ecosystem productivity ranging from 200-400 g C m^{-2} yr^{-1} (Aber and Melillo, 2001).

Studies of changing C stocks have shown that extensive green roofs have the potential to rapidly accumulate plant biomass over the short-term, especially if they are established using seeds or small cuttings, but total plant biomass plateaus at a low value relative to most natural vegetated ecosystems (Getter et al. 2009; Rowe 2011). Whittinghill et al. (2014) also found that green roof plots could sequester a small amount of C, though less than similar ground-level plantings.

Because of the low potential for long-term plant biomass accumulation on extensive roofs, long-term C storage depends mainly on the accumulation of organic matter in the substrate. Early research in Germany and the UK suggested an increase in substrate organic matter content over time (Köhler and Poll 2010; Schrader and Boning 2006), particularly for shallow, single layer extensive green roofs (Thuring and Dunnett 2014). Research in Michigan with newly established green roof plots planted from seed found similar results with substrate organic matter content increasing over 5 years (Getter and Rowe 2007; Rowe 2011). Recent research from France however found contrasting results with new green roof plots decreasing in organic matter content, suggesting the need for more comprehensive research on this topic (Bouzouidja et al. 2018).

Many studies have shown that green roofs can give rise to high concentrations of DOC in runoff water (e.g. Aitkenhead-Peterson et al. 2011; Beck et al. 2011; Berndtsson et al. 2009; Buffam et al. 2016). Carpenter et al. (2016) also measured hydrologic export fluxes of DOC and other chemical constituents for a green roof in Syracuse, NY. Based on several published studies, Buffam and Mitchell (2015) estimated hydrologic export from extensive green roofs varying from 3-31 g C m^{-2} yr^{-1} depending on the characteristics of the green roof and environmental setting. This is a large range of uncertainty but implies that hydrologic export is of importance to the net C budget of many green roof systems.

Results to date, both in North American research and globally, suggest that green roof ecosystems can serve either as a sink or as a source for C – with the distinction likely depending on the initial conditions (substrate organic matter content and type, and vegetation type and coverage), as well as local climate and roof hydrology. This is a fertile area for further research. Monitoring studies of organic matter content and plant biomass over time would be a simple, but logical next step to distinguish between roofs that are sinks or sources for C – and should be accompanied by direct process measurements to determine which mechanisms are most important for C exchange. Studies of C budgets in intensive green roofs with deeper substrate would also be informative – these roofs have much greater potential for C sequestration if shrubs or trees develop over time, but also incur a greater additional energy cost for construction. There is additionally a need to place such studies into context of the total carbon/energy budget for the given roof, including embodied energy and potential energy savings over the life cycle of the system (e.g., Engström et al. 2018; Kavehei et al. 2018).

Plant Research

There is no debate, *Sedum* spp. are the default species on extensive green roofs, and arguably most green roof systems, in North America and beyond. And that is for good reason. *Sedum* spp. are low-growing drought-tolerant ground covers that are succulent and many are evergreen (Snodgrass and Snodgrass 2006). This genus of plants is easy to propagate, and they live relatively long lives for perennials.

Sedum spp. will probably always be the most common choice for extensive green roof systems in North America. However, in isolation, they may not provide all the benefits desired or fit the palette of plants required for all applications of green roof systems. For example, many of our North American native pollinators may not be able to use *Sedum* spp. flowers for nectar or pollen sources, although there is evidence that some do already use *Sedum* spp. (MacIvor et al. 2015). Thus, depending on the wishes of the building owner, more pollinator-friendly plants, such as native plants, may need to be installed.

Scientists and practitioners across North America have been investigating additional options for green roof plants since the turn of the century (Bousselot et al. 2010; Ksiazek et al. 2014; Lundholm et al. 2010; MacIvor and Lundholm 2011; Monterusso et al. 2005; Schneider et al. 2014; Snodgrass and Snodgrass 2006; Sutton et al. 2012). There is a strong emphasis on native plant evaluations (Bousselot et al. 2010; Ksiazek et al. 2014; Lundholm et al. 2010; MacIvor and Lundholm 2011; Monterusso et al. 2005; Schneider et al. 2014; Sutton et al. 2012) with the results being mixed as Butler et al. (2012) points out.

In fact, in literature reviews by Dvorak and Volder (2010) and Cook-Patton and Bauerle (2012), the authors specifically call for the expansion of green roof plant evaluations as we have only evaluated a small fraction of the species available for use on green roof systems in North America. Unfortunately, few publications in the last half of this decade have been focused on this aspect of green roofs, despite the call for more from Dvorak and Volder (2010). This is likely due to the lack of funding for plant performance evaluations.

Large-scale plant species evaluations for use on green roofs is only one aspect of plant research that can be expanded upon in North America. The evaluation of specific regional plant communities (MacIvor and Lundhom 2011; Sutton et al. 2012) and life forms (Lundholm et al. 2010; Schneider et al. 2014) could also be expanded upon and should be tested in multisite research trials. Additionally, plant species evaluations with varying combinations of substrate depth, composition, and irrigation levels in multisite research trials will elucidate the way these factors interact in green roof applications.

Biodiversity

Green roofs can mitigate the negative environmental impacts of biodiversity loss in urban development. Yet, studies focus on maximizing performance at the expense of diversity through installed plant monocultures, or just a few species of *Sedum* spp., on extensive North American green roofs.

More recently, increasing biodiversity of green roof plant community structure has come into focus (Cook-Patton and Bauerle 2012; Dvorak and Volder 2010). Specifically, the use of native plant species on green roofs has been explored (Bousselot et al. 2010; Ksiazek et al. 2014; Lundholm et al. 2010; Decker et al. 2015) with mixed results (Butler et al. 2012). Native C_4 graminoid dominant and C_3 graminoid and forb dominant roofs in New York (Aloisio et al. 2019) and prairie grasses mixed with *Sedum* spp. in the upper Midwest (Liu et al. 2019a) have shown promise. In addition, choosing *Sedum* spp. based on phylogenetic and functional diversity rather than species richness alone enhances many ecosystem functions of green roofs (Xie et al. 2019).

Green roofs can also enhance urban diversity by providing habitat for a wide range of animal taxa (Coffman and Waite 2011). Not only do highly mobile native insects utilize green roofs, but apterous and soil-dwelling insects are colonizers (MacIvor and Lundholm 2011; Steck et al. 2015; Tonietto et al. 2011). Although, insect diversity on green roofs tends to lag behind species richness in nearby ground-level habitats (MacIvor and Lundholm 2011; Steck et al. 2015; Tonietto et al. 2011). Migratory and non-migratory bird species interact with green roofs through perching, foraging, or nesting (Partridge and Clark 2018; Washburn et al. 2016). Green roofs also support multiple species of bats in urban settings (Parkins and Clark 2015).

The understanding of biodiversity in conservation efforts has been examined by Williams et al. (2014) through six hypotheses commonly associated with green roof biological diversity. They determined, in large part, that researchers and practitioners are still developing a base understanding of most concepts such as rare species utilization, ground-based mitigation, and nativity for green roof organisms. More substantial evidence is needed from field studies in North America.

Examining biodiversity moving forward should continue to analyze physical and abiotic aspects of green roof systems (e.g., size, age, height, substrate depth, substrate, and plant heterogeneity, etc.) that influence the richness of species found therein (Aloisio et al. 2017). In addition, other aspects of diversity such as types and amount of microbial assemblages, which offer plants many protections against stressors (Fulthorpe et al. 2018; Hoch et al. 2019), should be fully examined. Lastly, attention should be given to the genetic diversity of green roof organisms to better determine the role these structures may play in conservation.

Ecomimicry

The mimicking of local ecosystems is popular in North American green roof systems and beyond (Nash et al. 2019). The large geographic expanse across a range of continental biomes and climatic zones creates extremely high ecosystem diversity that is offering opportunities for contextual experimentation. Dvorak and Volder (2010) argue contextual, or local, living roof systems can provide improved ecosystem services while better fitting within regional policies.

The highly distributed prairie and meadow ecologies are productive systems of study that have research sites across a longitudinal range in Minnesota, Nebraska, Wisconsin, Kansas, Oklahoma, and Texas (Sutton et al. 2012). Most of these studies focus on plant establishment and behavior. Bedrock bluff prairies have been studied by MacDonagh and Shanstrom (2015) in the upper Midwest for over a decade and demonstrate successful plant assembly and abiotic effects of local Minnesota ecosystems. The Minnesota studies list native plants and speculate on key abiotic variables such as supplemental irrigation. Local ecomimicry has been popular in botanic gardens and institutes including, prairies (Hawke 2015), semi-arid deserts (Schneider et al. 2014), and barrens (Best et al. 2015). Comprehensive establishment studies of upper Midwestern prairie species have been published in reports, including rating early-stage behavior, such as reseeding in 4-, 6-, and 8-inch depths, (Hawke 2015). Experiments using local native soils are occurring in Texas under a lens of restoration (Best et al. 2015).

The study of dryland and rock-based ecosystems first advocated by Lundholm (2006) remains the most popular system of exploration. Less studied are wetland systems which have been argued to possess greater ecological services (Song et al. 2013). The study of local ecologies may lead to an increased understanding of native and rare species and aid in the role of ecological novelty (Lundholm and Walker 2018). North America's size and diversity offers continued study of native ecosystems for green roof ecomimicry.

Biodispersal

Green roof systems can be an ecological resource to the surrounding landscape. Although very few studies address this concept directly, Coffman et al. (2014) explain that plants are self-seeding and being transplanted as a part of urban forest restoration practices from a green roof in Cleveland, Ohio. Decker et al. (2015) have demonstrated the dispersal of native species across a large green roof when originally planted in only a few locations. When matched with the at-grade growing conditions, it may be possible for green roofs to contribute to landscape restoration efforts. One project, the M6B2 Tower of Biodiversity in Paris (2016), France, is examining the role of green roof dispersal.

Depending on the species of bird, bee, and insect (Coffman and Waite 2011; Ksiazek et al. 2018) organisms may have the potential to nest and create viable offspring, yet some may be limited (MacIvor 2016). The focus of published studies in North America remains solely on the presence of these organisms and should begin to investigate the positive and negative impacts on the surrounding landscape.

Long-Term Dynamics

Green roof systems are built and designed to last for more than 40 years. However, we are just beginning to develop an understanding of how modern North American green roof systems change as they mature beyond their first decade of existence. Plants that are initially installed in the green roof system compete with each other, interact with a dynamic substrate that is subject to biogeochemical processes, and have to face competition from a constant supply of colonizing organisms. These complex temporal dynamics are likely to have a strong influence on the benefits derived from the green roof (Carlisle and Piana 2015) and, ultimately, how long the initial green roof plants will last. Therefore, establishing a more complete understanding of green roof succession may help us design or manage green roofs more effectively so that they maintain ecosystem services or even increase in value over time.

Studying the long-term dynamics of green roofs poses several challenges. Most importantly, it requires access to older systems and knowledge of their initial conditions. Secondly, knowledge about how or if the green roof systems have been maintained (e.g., weeded, fertilized, etc.) is required. To our knowledge, there are only seven peer-reviewed studies that have evaluated dynamics on roofs greater than 10 years old (Catalano et al. 2016; Gabrych et al. 2016; Köhler 2006; Köhler and Poll 2010; Mitchell et al. 2017; Schrader and Boning 2007; Thuring and Dunnett 2014). Most studies published on this topic have had to make compromises in some regard, either making assumptions regarding the initial design conditions or looking to establish correlations using large collections of roofs that vary in roof age as well as several other variables. Nevertheless, our understanding of long-term dynamics has grown over the last 20 years, with most work done in the last decade.

By far the majority of research on long-term dynamics has focused on the plant community. Plant species richness was negatively related to roof age in two studies (Köhler and Poll 2010; Thuring and Dunnett 2014), positively related in two studies (Catalano et al. 2016; Gabrych et al. 2016), and not related in two other studies (Köhler 2006; Mitchell et al. 2017). These contrasting dynamics point to the challenges associated with studying long-term dynamics across systems with very different initial planting, design, microclimate, and management strategies. Intriguingly, several studies have observed that roof colonizers such as ruderal plants and lichens (Catalano et al. 2016; Mitchell et al. 2017) may increase in dominance over time. These dynamics echo findings from studies performed by Dunnett et al. (2007) and Rowe et al. (2012) that tracked green roof plant succession in plots for 6 and 7 years, respectively.

Unfortunately, very few studies have reported changes in the physical or chemical status of the substrate over time. Köhler and Poll (2010) observed an increase in substrate porosity for modern extensive green roofs in Germany in the first 10 years following installation. In these same roofs, organic carbon content was approximately stable in the first decade but increased from 2 to 3% in the following decade. Schrader and Boning (2007) and Thuring and Dunnett (2014) also observed positive correlations between roof age and organic matter content. Studies by Köhler and Poll (2010) and Mitchell et al. (2017) both observed a long-term decline in the carbon to nitrogen ratio driven by positive relationships between roof age and nitrogen, with nitrogen inputs in one study exceeding nitrogen deposition in the region and suggesting substantial nitrogen-fixation (Mitchell et al. 2017).

Clearly there is a need to further evaluate how the plant community evolves, how animals/insects/birds colonize, and how the substrate changes as green roof systems mature after 10 or more years. While these areas are understudied, the following areas have received even less attention with regards to long-term dynamics and need to be evaluated moving forward to ascertain long-term green roof performance and ecosystem service implications: 1) how does green roof water retention change as the system ages; 2) what impacts does aging have on thermal dynamics for structures directly in contact with the green roof system and the surrounding environment; 3) how do microorganism communities change as the roof ages, and where do they come from; and 4) how does the initial design (e.g., slope, plant palette) and subsequent management regime (e.g., weeding, fertilization) impact long-term development?

Urban Food Production

As cities expand and climate change reduces the effectiveness of rural agriculture, urban areas are looking toward increased food production within their land areas. Urban agriculture can increase city resilience, reduce transportation costs and the associated carbon footprint, provide economic advancement, increase social and educational opportunities, and provide produce in food-insecure areas (Buehler and Junge 2016; Hammelman 2019; Ugai 2016). Rooftop and wall gardens have the added benefit of utilizing unused space with limited uses (Hammelman 2019).

Intensive rooftop gardens increase the diversity of potential crops, but they are limited by weight-load restrictions, installation requirements, and labor needs (Ackerman et al. 2011; Whittinghill et al. 2013). Intensive rooftop gardens better serve profit-driven commercial ventures, as the sale of produce can offset the initial cost of the system (Buehler and Junge 2016).

Commercial rooftop food production may also incorporate greenhouse, hydroponics, or other soilless production methods. Commercial rooftop farming can afford the upfront price of rooftop farming, as well as provide the expertise, skill, and manpower needed to produce significant amounts of locally grown food (Buehler and Junge 2016; Ugai 2016). The use of hydroponics and greenhouses instead of open-air farms is increasing. Open-air farms can provide a more diverse production, but hydroponic systems may supply food year-round. Hydroponic systems are not innately sustainable, but most current systems use multiple sustainable techniques, such as energy efficiency measures, chemical-free production, and water recycling (Buehler and Junge 2016).

Extensive rooftop gardens include the use of ground plots or planters. Shallow-rooted vegetables and herbs – tomatoes, cucumbers, chives, basil, and beans – have produced similar production rates in extensive rooftop systems compared to on-ground plots (Whittinghill et al. 2013). Green roof substrates are low in organic matter so nutrient supplementation is often required for urban rooftop food production. Selective treatments of synthetic fertilizers may improve yields, but caution is required to prevent excessive stormwater runoff contamination (Walters and Midden 2018; Whittinghill et al. 2016).

Rooftop gardens share many of the same benefits of ground-level urban agriculture, but it does have unique challenges: accessibility and safety concerns, greater installation costs, harsher conditions, substrate depth limits, and increased labor and expertise requirements (Ackerman et al. 2011). Ground-level agriculture is commonly at risk of being lost to development, vermin, or vandalism. Rooftop gardens are often protected from these risks, offering an untapped space to bring more food production to urban areas (Hammelman 2019).

Rooftop gardens may not be the desired solution for low-income and food-insecure communities, however. When Toronto attempted to replace ground-level agriculture with rooftop gardens in low-income areas, the urban farmers were dissatisfied with the exchange. Rooftop gardens required more costs, time, and labor than their previous ground-level gardens. Policies designed to improve urban agriculture that fail to consider the barriers to low-income communities will lead to uneven distribution of farms on all levels (Hammelman 2019).

North American research of green roof food production has been primarily conducted at universities and in large metropolitan areas, such as New York City and Toronto, within the last decade. More research is needed in the productivity and feasibility of rooftop gardens in other regions of North America, especially when it comes to the suitability of various produce and irrigation and nutrient management requirements. Information about the role rooftop gardens can have in low-income areas and how policies can be written to improve the desirability of these projects is lacking. It is also unclear if residents in low-income areas will choose to utilize or consume produce from rooftop gardens. More knowledge is also needed to discover how rooftop gardens may provide job opportunities for various locations throughout the urban environment (Ackerman et al. 2011). Commercial rooftop farming can increase urban sustainability if more research is conducted on how to connect the farm and building through the use of waste heat, greywater, or gas exchange (Buehler and Junge 2016).

Synergy with Solar Panels

There is competition for space on rooftops. Building owners are often asked to decide if they want to invest in renewable energy such as solar panels or provide green space on rooftops. However, it does not have to be an either/or decision; green roofs and solar panels blend well together on rooftops. In fact, it can be said that these two green technologies have a synergistic relationship if the term 'synergy' can be applied to the interaction between living systems and technology.

This synergistic relationship means that both green roofs and solar panels may perform better by coexisting on rooftops. Green roofs cool ambient rooftop temperatures in summer and with cooler temperatures solar panels produce more energy (Alshayeb and Chang 2018; Gupta et al. 2017; Hui and Chan 2011; Köhler et al. 2007; Ogali and Sailor 2016; Sherba et al. 2011). Solar panels on green roofs shade plants, therefore reducing evapotranspiration rates and mitigating water stress (Alshayeb and Chang 2018; Bousselot et al. 2017; Köhler et al. 2007; Ogali and Sailor 2016). Solar panels also moderate extreme temperatures on rooftops to the benefit of plants in both summer and winter (Bousselot et al. 2017).

Regional climatic conditions significantly affect how impactful the synergistic relationship is between green roof and solar panels. In general, rooftop vegetation provides more cooling benefits in hot and dry climates than in cool and humid climates (Alexandri and Jones 2008). Therefore, we expect that this climatic phenomenon would also apply to green roof systems that happen to have solar panels on them.

In temperate Kansas, with hot and humid summers, the greatest benefit of having plants underneath solar panels for energy production occurred in the hottest months of June and July (Alshayeb and Chang 2018). This result is similar to research findings in Portland, Oregon, which has dry and warm (but not hot) summers, although the benefit was less (Ogali and Sailor 2016).

The overwintering of plants in the cold and dry winter conditions of Colorado was greatly improved in the shade cast by solar panels and the substrate moisture was higher in shade under hot and dry summer conditions (Bousselot et al. 2017). Despite the relative difference in humidity levels between Kansas and Colorado, it was noted that *Sedum* spp. thrived underneath the shade of solar panels (Alshayeb and Chang 2018; Bousselot et al. 2017).

For the most part, all the published research on the interaction between solar panels and green roof systems has been published in this century. Things that remain to be evaluated are the influence of varying types of solar panels, including semi-translucent and translucent panels, the way that solar panels are placed or mounted on the roof, and how they respond to the cooling by varying types of green roof systems. While Ogali and Sailor (2016) established that distance between the panels and the plants matter a great deal to the realization of benefits, that work can certainly be taken further to discover the ideal distance between the two technologies. Finally, the relative influence of climatic factors such as temperature and humidity on the co-benefits of solar panels and green roofs needs to be evaluated in multiple regional locations in a replicated trial to validate research results.

Financing Nature-Based Solutions

Cities play a central role in planning and investing in the greening of urban infrastructure. More people now live in cities than rural areas, and it is projected that 68% of the world's population will be living in cities by 2050 (United Nations 2019). Cities currently occupy 2% of the total landmass of the planet, yet they consume two-thirds of the global energy and produce two-thirds of the global greenhouse emissions (Khatib 2012; Merk et al. 2012). City leaders are finding that nature-based solutions (NBS) are one of the best strategies to help solve multi-faceted challenges, such as combined financial, political, infrastructural, and regulatory constraints.

NBS are defined by the International Union for Conservation of Nature (IUCN) as "actions to protect, sustainably manage, and restore natural or modified ecosystems, that address societal challenges effectively and adaptively, simultaneously providing human well-being and biodiversity benefits" (Cohen-Shacham et al. 2016), and green roof systems are part of the NBS strategies (Cohen-Shacham et al. 2016; Maes and Jacobs 2017). Rather than depleting scarce natural resources, NBS in the urban planning process can offer regenerative solutions; easily adapt to climate and environment and are therefore climate resilient; achieve climate and CO_2 reduction goals for cities; can be set up as circular economies; are cheaper than grey infrastructure solutions (non-circular economies); increase biodiversity; mitigate UHI; slow and clean water runoff; improve livability and human health; encourage collaboration and co-creation for communities; promote urban agriculture; increase real estate value and market potential revenue (Millard et al. 2019; Tolderlund 2019).

Finding ways to finance NBS, and the importance thereof, has been well documented over the past decade, including studies with a focus on practices and challenges of financing green urban infrastructure and NBS (Merk et al. 2012; Sweatman and Managan 2010); removing and eliminating real (and perceived) obstacles to NBS and green infrastructure solutions (Dunn 2007); and access to various types of NBS financing, such as green mortgages (a mortgage to specifically buy or renovate a 'green' building) (Claus and Rousseau 2012) and PACE (Property Assessed Clean Energy) financing (Managan and Klimovich 2013).

Additionally, over the past decade, there have been studies with a focus on determining the financial impact of the implementation of green roof systems based on energy savings (Carter and Keeler 2008; Celik and Ogus Binatli 2018; Clark et al. 2008; Nurmi et al. 2013), increased property value (Bianchini and Hewage 2012; Porsche and Köhler 2013), increased longevity (e.g. double the lifetime) of the roof (Claus and Rousseau 2012; Porsche and

Köhler 2013), and insulation and energy efficiency (Carter and Keeler 2008; Claus and Rousseau 2012).

In a literature review of studies that calculate the economic impact of green roof systems based on life cycle analyses, Celik and Ogus Binatli (2018) point to the importance of the timeframe looked at, such as 30-year life cycle (Blackhurst et al. 2010); 40-year life cycle (Clark et al. 2008; Mullen et al. 2013); 50-year life-cycle (Sproul et al. 2014); and 70-year life cycle (Porsche and Köhler 2013), and conclude that economic benefits accumulated to greater amounts, the longer the time frame.

Despite much emphasis on documenting the economic benefits of NBS and green infrastructure, there are still many hurdles and barriers to implementation in both the private and public sectors. Toxopeus and Polzin (2017) argue in a literature review of ~100 qualifying NBS research articles published between 1998 and 2017, that the main barriers to implementation are related to the lack of financial sources available (both public and private) to tap into, as well as obstacles associated with determining the actual value of NBS, including value proposition, value delivery, and value capture. At the green roof level, a study by Claus and Rousseau (2012) points toward the necessity for financial subsidies for green roofs for private building owners, such as, for example, green mortgages. Merk et al. (2012) point to the need for engaging in new flexible and co-operative private-public finance models.

Additionally, Merk et al. (2012) point towards a series of policy recommendations to help finance and further implementation of NBS, such as removing barriers at the local government level, maintaining a holistic approach to the entire tax and benefit system, keeping policy packages simple as complexity makes it more difficult and increasing the risk of unintended or unrealistic incentives as a result. Furthermore, Merk et al. (2012) recommend tapping into new sources of finance, such as: making carbon finance more accessible for cities, internalizing financing of development projects for infrastructure needs for new developments, and cooperation at the national-local level to encourage cities to network between each other as well as working with central governments when negotiating private sector financing.

Toxopeus and Polzin (2017) conclude in their literature review that different types of NBS need different levels of finance and business models. In order to achieve balance in incentives and to more effectively and efficiently value different payoffs, Toxopeus and Polzin (2017) recommend that financing ideally should come from a diverse group of public and private entities.

Great potential for future studies on financing NBS includes the expansion of the framework for how cities identify the ideal business model and type of finance for urban green infrastructure, NBS and green roofs (Toxopeus and Polzin 2017). There are existing financial strategies that cities use to attract private finance for NBS, such as: tax increment financing (using future tax revenues), development charges (impact fees), value capture (taxes of the increase of real estate value caused by nearby development), carbon finance, loans and bonds, and public-private partnerships (where the long-term risk is moved over into the private sector instead) (Merk et al. 2012). Yet studies that provide clarity on strategies and business models, as well as case studies that successfully have financed NBS (Millard et al. 2019), can contribute to the overall knowledge on how to finance NBS.

CONCLUSIONS

Of the 175 peer-reviewed manuscripts cited in this document, only three were published prior to the year 2000. That fact alone suggests that the research surrounding green roofs has progressed tremendously over the past two decades. While the focus of this work is North American green roof research, the results from other parts of the world help inform and guide the efforts of North American researchers and are, therefore, included in this review.

Future Research Needs Summary

Despite the large amount of published research on green roofs within and beyond North America, many research needs remain. The academics in the RACE in Living Architecture represent important disciplines conducting living architecture research, but the following research needs highlight the necessity for even more disciplines to be involved. The research needs also highlight the importance of collaborative and intentional research designs.

- UHI
    - Determine the optimal spatial configuration of green roof applications to maximize the mitigation of UHI.
    - Investigate green roof species and plant combinations for their capacity to cool their surrounding environments.
    - Evaluate the role substrate depth and composition have in mitigation of UHI.
- Energy
    - Evaluate further plant and substrate combinations, especially as they relate to evapotranspirational cooling.
    - Evaluate energy generation (e.g., solar panels) in combination with living architecture.
- Stormwater
    - Evaluate long-term plant and substrate combinations and their effects on stormwater.
    - Evaluate technological tools to help designers select components of green roofs to optimize stormwater benefits.
- Carbon
    - Evaluate atmospheric carbon dioxide exchange and total carbon budgets in green roof systems.
    - Monitor long-term organic matter and biomass accumulation.
    - Evaluate if green roof systems are sinks or sources of carbon.
    - Evaluate the impacts of substrate depth and plant choices (e.g., woody plants) for carbon sequestration.

- Plants
    - Evaluate plant performance in long-term, large-scale, and multi-site trials.
    - Evaluate ecoregional plants by community and life form.
    - Evaluate plant interactions with other components of green roofs.
- Biodiversity
    - Evaluate abiotic and biotic aspects of green roof systems.
    - Evaluate substrate microbial populations and system response.
    - Evaluate the influence of genetic diversity.
    - Evaluate the impact of using wetland, native, and rare plant species systems.
- Long-term dynamics
    - Evaluate succession and evolution on green roofs.
    - Evaluate micro- and macrofauna habits.
    - Evaluate benefit valuation and system characteristics over time.
- Food production
    - Evaluate food production on rooftops in new regions.
    - Evaluate additional irrigation and fertilizer regimens.
    - Study the intersection of green roof food production with food deserts and policy.
    - Incorporate consumer food use patterns.
    - Evaluate the potential for job creation.
    - Evaluate integration of rooftop production into building systems.
- Solar panel synergy
    - Evaluate new panel types.
    - Evaluate appropriate panel height.
    - Evaluate species cooling effectiveness.
    - Evaluate regional and climatic differences.
- Financing NBS
    - Evaluate and find new business models and finance options for NBS.
    - Publish more case studies on financing NBS.

Future Capacity for Investment and Funding

While there has been substantial research conducted that has improved green roof practice in North America, there remain many important but unanswered questions that, if answered, could propel the future growth of living architecture installations. However, the expansion of innovation and research in green roofs and green infrastructure requires concerted and consistent funding. As the North American academics associated with RACE in Living Architecture, we are advocating for sustained financial support from private, public, local, federal, and international organizations. Unbiased, peer-reviewed scientific inquiry supports all facets of the green roof industry. Therefore, supporting this research should be a primary goal of all of those associated with the green roof industry.

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