RESEARCH PAPER

Productive Blue-Green Roofs for Stormwater Management

Kristiina Valter Mai*

Toronto Metropolitan University (TMU), Canada
*Correspondence: E-mail: kvmai@ryerson.ca

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Abstract

Green roofs have been used around the world for centuries, and have been adapted to modern urban buildings. Many cities have now adopted a green roof bylaw in recognition of their environmental benefits, including stormwater management. Despite this requirement, if green roofs are poorly designed, they may quickly become ineffective or counterproductive. In this paper, features of green roofs that are important for sustained environmental benefit are highlighted with a focus on water demand and management. Blue roofs use specialized retention layers to delay stormwater run-off or retain it for evaporation. Blue and green roofs can be combined to grow productive, or edible crops and this use can have synergistic benefits. This paper describes case studies and testbeds of various combinations of green and blue roof sublayers with edible and non-edible plants. Design parameters are considered and monitoring and automation systems are described.

Keywords: green roofs, blue roofs, storm water management, water retention, evapotranspiration, productive green roofs, ecological farming, urban agriculture, rain water harvesting

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1. *Introduction*

Environmental concerns have been a major topic in science and media as well as among the public for many decades. While awareness and public pressure has been high, government actions have been limited by economic pressures, and thus meaningful action is slow to gain traction. Industry actions are paradoxically driven by consumer demand. The limited real action has resulted in obvious climate change effects, such as extreme temperatures, forest fires, droughts, floods and storms. The impacts of these events take a serious toll on the people and on all life in the affected region.

This challenges us to innovate based on our current situation, making incremental achievable changes and taking steps towards a lower environmental footprint as much as possible. For example, upon observing the expanses of concrete in growing cities around the world, we recognize the importance of nature in these artificial environments that are rather hostile to human wellbeing. An important effort is the purposeful introduction of plants, gardens, meadows and even farms both indoors and outdoors wherever possible and imaginable: on balconies, in yards, on vertical surfaces, and on rooftops.

Rooftops represent a tremendous amount of valuable real estate especially as urban areas continue to expand. These largely unused and predominantly horizontal surfaces can be utilized for many beneficial purposes, such as for energy generation through solar panels, for stormwater management and for plant growth. This paper investigates the opportunities of rooftops to make a multi-dimensional impact towards climate change mitigation.

2. *Green and blue roofs*

2.1. Green roofs

A green roof refers to a layer of vegetation on a rooftop, with the required sublayer(s) for waterproofing and other performance characteristics [1]. Although green roofs have been used for centuries around the world, for example on thatched and moss-covered roofs, modern building structures necessitate specifically designed waterproofing membranes and a certain structural capacity to ensure building integrity over time. Green roofs provide additional insulation to the building and introduce plant life to the environment with inherent benefits such as reducing pollution and atmospheric carbon, reducing the urban heat island effect in hot temperature conditions, promoting biodiversity, retaining stormwater and more.

There are two main types of green roofs: extensive and intensive, with many variations of each. Extensive green roofs can be implemented on a wider variety of roofs due to their shallower soil or growing media and therefore reduced loading on the building structure. While this type of roof is typically less expensive, it restricts the selection of plant species and is limited in its stormwater performance and insulation properties. Intensive green roofs can permit deeper soil or growing media and thus a greater diversity of plants, including potentially productive food crops and even trees. Semi-intensive green roofs are a blend of these two green roof types [2, 3].

Design trade-offs include building constraints, cost, safety, aesthetics, environmental sustainability, climate resilience including tolerance of the more extreme rooftop microclimate, and interaction with building users which could benefit their health including mental health. Green roofs, with their multiple benefits, are now mandated in many municipalities [4]. However, green roofs can fail to satisfy design expectations in two basic ways: by causing damage to the building, or by failing to perform as a green roof. In order to prevent the former, proper structural analysis and construction are required as well as suitable

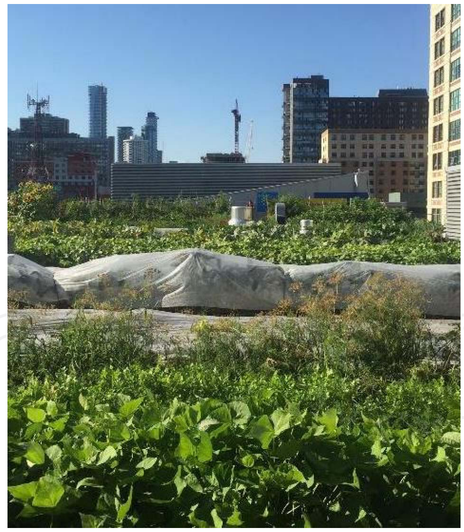

Figure 1. Intensive green roof urban farm. Toronto Metropolitan University (TMU), Canada.

waterproofing membranes. Failure to perform as a green roof can consist of a failure in any of the expected properties, such as plant growth, aesthetics, stormwater management, insulation, or all of these [5]. These failures can result from poor maintenance but can often be traced back to the design and possible cost reduction priorities. If too much or too little water is retained within the growing media, the plants will not survive.

Green roof designers can incorporate both extensive and intensive areas and may include public access and even community agriculture. Deeper beds can be strategically placed above supportive vertical load-bearing columns in the building structure to satisfy structural requirements. Green roof agriculture can vary in scale, ranging from container plants to urban farms. Ecological farming practices are an ideal way to ensure plant and soil health while optimizing environmental benefits. These practices include mulching, composting, companion planting, crop rotation, row covers, winter cover crops and many other techniques, instead of chemical sprays and fertilizers. Such ecological practices also reduce the reliance on irrigation, which we will discuss later in this paper. An example of a productive or agricultural green roof in Toronto is the Ryerson* Urban Farm [6]. Figure 1 shows this green roof during the summer growing season, and figure 2 shows winter cover crops and mulching in January.

2.2. Container gardens

The Ryerson* Urban Farm has also used container growing in a small section of the rooftop. This method provides a high level of flexibility as the containers can be moved

Figure 2. Ecological growing practices of winter cover crops and mulching in January at Ryerson* Urban Farm, Toronto Metropolitan University (TMU), Canada

from one location to another and are not permanent installations. They can be used in small spaces such as on balconies, and the layout can be easily changed over time.

Over the years, container plant growth practices have led to effective innovations in container design. For example, the Sub-Irrigated-Planter (SIP) design uses two compartments as shown in figure 3. The lower portion of the container is a water reservoir which is filled through a tube and which has a drainage port near the top of this reservoir section. The upper portion of the container has the soil/growing media and plants. A wicking fabric and separation layer keep the soil in the upper section while drawing water from the reservoir up to the growing media and plant roots. Water is drawn upward by the hydrological conditions of the soil and especially by the absorption of the moisture by the plant roots [7].

2.3. Blue roofs

Blue roofs are designed for stormwater management to hold water, which is released through delayed run-off drainage or evaporation. The water retention can be provided by media such as soil, or by specially designed retention reservoirs [8]. As can be expected, blue roofs also require careful attention to waterproofing and structural capacity to support the weight of the water on the roof.

Of particular interest is in maximizing the potential of blue roofs to not only retain and/or detain the water, but to put it to productive use for plant growth. Plants on the other hand, offer the opportunity to absorb and retain some moisture within their structure, and also eliminate some of the water to the atmosphere through evapotranspiration (ET). By combining blue roofs with green roofs,

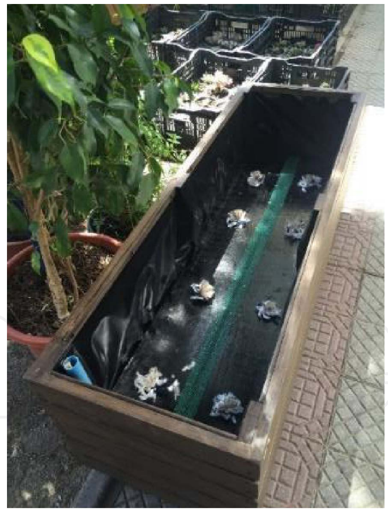

Figure 3. An example of a Sub-Irrigated Planter (SIP) container showing the membrane separating the water reservoir from the upper compartment where the soil and plants will be added. The wicking material which allows plant roots to draw water from the reservoir to the soil and the roots can be seen connecting the two compartments. The watering tube is in the front left corner.

the stormwater management potential of both blue roofs and green roofs is enhanced by incorporating the plants to hold, delay and eliminate water run-off [9].

Plant selection can play a role in the roof system design to optimize stormwater performance considering both the retention aspects and evaporation in addition to the ET enabled by green roofs [10]. Evaporation and ET have a cooling effect on the building, which is another environmental benefit that both blue roofs and green roofs can provide.

2.4. Blue-green roofs

Blue-green roofs represent the synergistic benefits of both blue roof and green roof technologies. Retained water supports the plant health and the plants help to retain and remove stormwater from the municipal stormwater management system [11].

The concept of combining green roofs and blue roofs is often implemented in a manner similar to the SIP container design. A wicking layer is provided such as in the SIP containers to bring the moisture up to the atmosphere or to the plant growing media/soil. Figure 4(a) shows an example of a wicking layer [12] and figure 4(b) shows how this layer can be situated between a drainage layer (in this case gravel) and a retention layer, which is the reservoir below.

The gravel can also provide necessary ballasting in rooftop applications where wind uplift is a major design factor. Design trade-offs with blue-green roofs include

(a) (b)

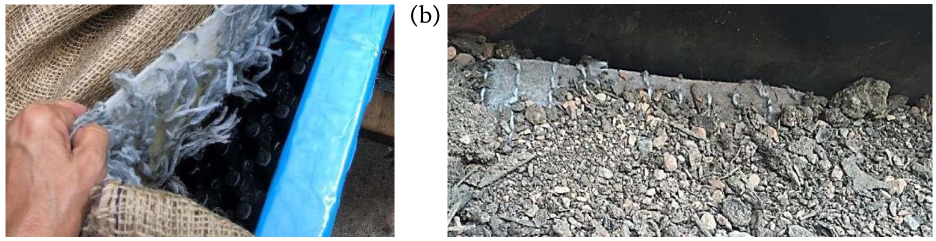

Figure 4. (a) A commercial patented wicking fabric [12] for drawing moisture from the water reservoir upward for plants and/or evaporation through the layers above. (b) The wicking fabric can be placed under a drainage layer or ballast layer such as the gravel shown here for green, blue and blue-green roofs.

structural constraints, cost, safety, aesthetics, environmental sustainability, climate resilience, and building user requirements and benefits.

2.5. Green roof urban farms

Often known as productive green roofs, green roof urban farms can provide additional benefits including local food production. Factors such as agricultural maintenance and harvesting (personnel and systems) and soil stewardship represent important considerations in these system designs. Figure 5 shows the Andrew and Valerie Pringle Environmental Green Roof at Ryerson University*. It was originally designed with non-edible plants in 6″ of growing medium. In its conversion to the Ryerson* Urban Farm, the existing soil was mounded to form rows and to provide a planting depth of 12″, which together with ecological farming practices has resulted in healthy, nutrient rich soil. This farm is now home to the Ryerson* Urban Farm Living Lab; it spans $\frac{1}{4}$ acre and can produce 10,000 lbs of produce in a growing season [6].

2.5.1. Irrigation

An important requirement for agriculture is proper soil moisture content or water supply for the plants. This can represent an environmental burden in itself especially in dry areas or in periods of drought and in areas where water is withdrawn excessively from underground resources [13]. Where municipal treated water is used, this creates an added environmental burden associated with water treatment.

Ecological growing practices reduce the environmental footprint of agriculture including the irrigation required. Mulching the soil conserves moisture, companion planting increases plant resilience, and taller plants can provide shade to reduce evaporation. These and other ecological practices can be employed in green roof urban farms.

Additionally, environmental practices should also include rainwater

Figure 5. The Ryerson* Urban Farm, Toronto Metropolitan University (TMU), Canada.

harvesting [14]. This is challenging on a roof because of the structural and spatial limitations, and also because a vertical height is required to allow the water to be collected into the reservoir and then subsequently drained from the reservoir onto the green roof surface. The blue-green roof design can facilitate rainwater harvesting as described above by providing a retention reservoir and passive wicking to move the water back upward against gravity for plant use. If neither an elevated reservoir nor a wicking system is possible, then the collected water can be pumped back up to the roof surface. If pumping is necessary, then it is recommended that it be powered through renewable energy such as through solar panels [15]. Manual watering is a good option with available labour if done consistently; it encourages observation of the plants and the rooftop conditions.

2.5.2. Run-off

In urban agriculture, over-irrigation or pesticide/herbicide use is harmful to the environment and puts additional loads on waste water treatment plants. Regarding run-off water quality, the inherent filtration properties of soil can remove impurities in rainwater, however, agricultural run-off can introduce nutrients and micro-organisms into the waterways that can be disruptive to the natural water ecosystem. Therefore water run-off monitoring is advisable, and research work on this aspect is important. However with blue-green roof system designs, a net-zero water outflow may be achievable in which water from the blue roof reservoir is fully retained and used by the plants or released to the atmosphere through evaporation or ET, thereby eliminating run-off.

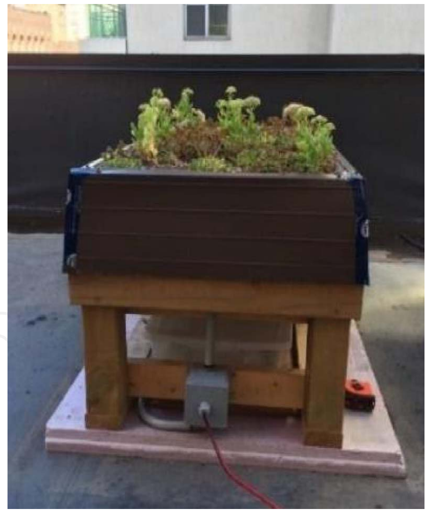

Figure 6. Green roof test module with reservoir to capture run-off and load cell instrumentation to obtain evapotranspiration values.

3. Evapotranspiration and retention for stormwater management

Green roofs and blue roofs have inherent stormwater management characteristics because of their capacity to retain water and delay or prevent its release into the urban water management system. Some cities have combined sewer and wastewater infrastructure and others have separate systems. Both of these have important limitations especially in stormwater management [16]. By taking some of the load off of these systems during heavy rain events, wastewater processing costs, sewage overflows and street and basement flooding can be reduced.

In an ongoing study, we have monitored the performance of various roof system designs in small modules of approximately 2′×3′ size on a downtown Toronto rooftop. Figure 6 shows one such module and system setup. The plant growth unit simulates a commercial extensive green roof, consisting of hardy succulent plants such as sedums, a certified green roof soil blend, a drainage fabric and a minimal water retention layer with a drain for any excess water. An additional reservoir to capture water draining from the module is located below it, and the module is instrumented with load cells to monitor the changing weight of the unit as rainwater enters and leaves the module.

Along with this simulated extensive green roof, an extensive blue-green roof, a blue roof without the green roof aspect, a productive intensive green roof and a productive intensive blue-green roof were evaluated with similar modules. Storm water retention and ET were monitored by continual logging of the module weight and by measuring the water drained into the reservoirs. After a major storm event it was found that the productive blue-green roof module had retained all of the stormwater ie. no water had drained into the reservoir below, whereas the other modules had varying amounts of stormwater run-off after the event [17].

4. Monitoring and automation

Technology can be beneficial in the maintenance of a blue and/or green roof system. It can serve in monitoring the condition of the materials and plants as well as automation of irrigation [18]. Technology should not replace human inspection and maintenance and it is important to include the "human in the loop" with automated systems design. Aside from normal maintenance and inspection requirements, human attention is particularly important when dealing with living organisms such as plants.

Data collection is important for thorough analysis, trend tracking and process improvements. For example, quantitative data on soil conditions is important for agricultural plants [19]. In developing an internet and mobile data logging system for productive green roofs, important parameters were determined to include soil moisture, temperature and pH. These metrics can be collected by an array of sensors installed permanently in the grow beds or by manual probing regularly or as needed [20].

In developing green roof information technology systems, full consultation with the operational farming team is essential to ensure that the most useful information is collected and to implement the most suitable data collection system and user interface. A complete system could include permanent data logging collected locally or transmitted to a cloud-based server. If internet uploading is enabled, the data could be accessible remotely for analysis and monitoring. Figure 7 shows a system diagram developed by students at Ryerson University* [21]. Ultimately these data inputs can drive actuators to activate irrigation valves as needed.

Implementation of rooftop sensing, automation and control systems has its own important design and planning considerations. Distributed sensors permanently installed in the growing media can be disturbed by farming operations. Regular inspections of the sensors and systems are also very important given the harsh weather conditions on rooftops. Not only are green roofs outdoors exposed to the elements, rooftops are exposed to more intense winds and greater temperature extremes than ground level environments. Also networking design should consider the availability of internet access on the rooftop including wifi range and signal strength.

The system shown in figure 7 used a Bluetooth transmitter to communicate with a mobile phone. In order to receive the data, MIT App Inventor was used to develop an

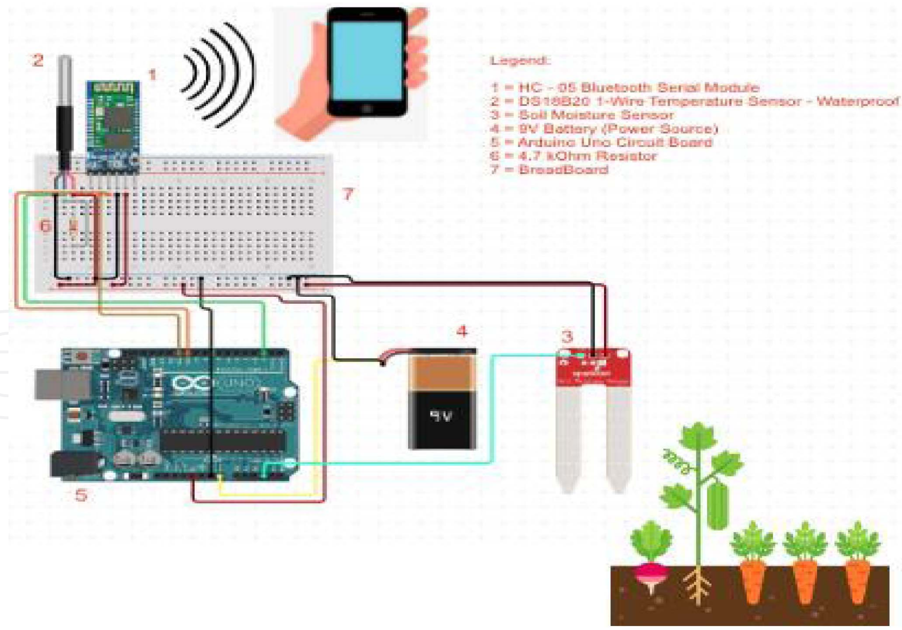

Figure 7. Soil monitoring and data logging system design [21].

Android mobile phone app to communicate with the Bluetooth transmitter. The data collected on the phone could then be relayed to a cloud-based server and/or transferred to a computer. The data were made accessible on the internet through a custom designed website-based interface designed with Wordpress 5.0. The database was managed with Sequential Query Language (SQL) and the data were configured with a Python script. Users could search for specific plants and obtain the temperature, soil moisture and pH values by date [21].

5. Conclusions

Green roofs can have tremendous environmental benefits, supplying ecosystem services across many environmental issues including stormwater management, temperature moderation of the urban heat island and building insulation, biodiversity, aesthetics and human health and wellbeing. Climate change effects such as flooding and droughts around the world highlight the importance of distributed stormwater infrastructure, which can be provided across entire urban areas by green roofs and blue roofs. Green roofs have the additional benefit of bringing plant life into the urban environment, including the potential for local food production. However, if these are implemented without attention to the environmental design aspects then cost optimization can lead to environmentally unfriendly outcomes rather than the intended benefits.

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Key recommendations addressed in this paper include: water retention capacity in the growing media and/or sublayers, use of ecological growing practices including soil enhancing cover crops, composting, mulching and row covers, and rain water harvesting where possible. Retention layers promote stormwater management synergistically with plants to delay and reduce runoff. Along with the use of technology, including soil moisture monitoring and automated irrigation systems, human attention remains important to ensure that the plants and the building infrastructure are kept in optimal condition.

Conflict of interest

The author has no conflict of interest with this work.

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