Towards a performance-based approach for multifunctional green roofs: An interdisciplinary review

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ABSTRACT

Green roofs have the potential to offer numerous ecosystem services; however, they are rarely designed to achieve them. Instead, design is restricted by perceived structural and maintenance constraints, which consequently diminish the achievable benefits. For green roofs to improve sustainability and resilience of cities, their design should match their promised multi-functional application using performance-based design. The first step towards a comprehensive performance model is to synthesize design recommendations across disciplines to identify synergies and trade-offs in design objectives for multiple benefits. This study discusses design strategies that could alter the energy and water balance in the green roof in order to attenuate urban stormwater, increase building energy performance, mitigate urban heat, and improve the output of solar panels placed on top of green roofs. These benefits are mathematically linked to quantifiable processes (discharge rate, water content, evapotranspiration, sensible heat, net radiation, insulation, and thermal mass), forming the foundation for a performance-based design model. Design recommendations are then summarized for each process, followed by a discussion of synergies, trade-offs, and research needs that arise when green roofs are designed to achieve multiple functions. Selecting vegetation with high leaf area and albedo improves multiple benefits without affecting structural constraints, whereas choosing plants with low stomatal resistance leads to trade-offs between higher evapotranspiration and higher irrigation requirements. Trade-offs in substrate depth and properties including organic matter and moisture are also apparent. Interdisciplinary collaborations are needed to simulate and optimize design parameters based on stakeholder preferences related to co-benefits and constraints.

1. Introduction

From urban heat island effect to pluvial flooding, cities are faced with a growing list of environmental challenges. This list includes addressing a considerable energy demand that must eventually be met using sustainable technologies, like rooftop solar panels, as well as adapting to the effects of climate change, such as more intense rainfall, drought, and extreme heat [1,2]. Due to the scale and urgency of these problems, innovative and integrated solutions that can resolve multiple urbanization challenges at once are required [3].

Green roofs, which are engineered rooftops that sustain vegetation, have been suggested as one such “nature-based” solution [4] to improve urban sustainability and resilience. They can provide multiple ecosystem services [5–8], including reducing urban stormwater runoff [9], decreasing the temperature of cities [10], diminishing the energy consumption of buildings [11], and more recently, increasing the efficiency of rooftop solar panels due to their cooling effect [12]. Green roofs also have the capacity to improve biodiversity [13,14], sequester CO₂ [15], reduce air pollution [16,17], and dampen noise [18,19]. These co-benefits are relevant decision factors that could increase the potential to disseminate green roofs throughout cities [20].

Despite the numerous co-benefits attributed to green roofs, they are rarely designed to achieve them [5]. Existing green roof design guidelines [5,21] favor design properties (e.g., vegetation and substrate characteristics) that would minimize static loading, maintenance, and cost [21] and rarely consider whether these recommendations would lead to the promised co-benefits. As a result, most green roofs are extensive (soil depth less than 20 cm) [22], not irrigated, and intended for aesthetic appeal. Substrate depths can even be restricted to a few centimeters and plant species are then selected for their ability to survive in shallow depths with low water and nutrient availability [23–27]. Sedums, a type of succulent plant, are the most common green roof vegetation for these reasons [26]; however, they have been shown to retain nearly the same amount of runoff as bare soil [28,29] and cool rooftops less than other species [30].

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In order for green roofs to systematically improve urban sustainability, many recognize that the design process should evaluate environmental performance objectives [25,31,32] alongside structural and maintenance constraints. Several studies have reviewed modeling and field experiments that assess individual performance objectives at the building scale (e.g., stormwater attenuation [9,33,34], heat mitigation and energy savings [6,10,11,35–37], and pollution and climate change [38]) or the processes (e.g., evapotranspiration [39]) and the design properties (e.g., materials [40] and vegetation [41,42]) that influence these objectives. However, few studies have reviewed multiple green roof co-benefits [5,43], and these studies did not consider trade-offs or preferences for design properties that maximize these co-benefits. Further efforts are still needed to continue progress towards performance-based design of green roofs, which ensures design properties are evaluated holistically with respect to multiple performance objectives.

The present work advances this goal by providing the foundation for a multi-objective, performance-based design model for green roofs. This is accomplished first by associating co-benefits to specific performance objectives and to the physical processes that influence them (Section 2). Second, the mathematical formulation is presented that links these physical processes to each other and to the green roof design properties (Section 3). Finally, the literature is summarized to evaluate how changes in design properties would alter different performance objectives (Section 4) and to identify synergies, trade-offs, and future research needs (Section 5) that arise when green roofs are designed to achieve multiple functions. As a first step, this review is limited primarily to roof scale studies of extensive green roofs that evaluate the effect of design parameters on four co-benefits: stormwater runoff attenuation, building thermal performance, urban heat mitigation, and rooftop solar panel output improvement.

2. Background

2.1. Current green roof design characteristics

Green roofs are primarily composed of three layers: vegetation, engineered media (substrate), and a waterproof membrane (impermeable liner) that prevents water from entering the building. Between the impermeable liner and media, some roofs also include a root barrier, which prevents roots from piercing the liner; a filter layer, that separates media particles; and/or a water retention layer, which retains additional water available for plant uptake [44–46]. Water drains from the bottom layer along the roof slope (typically less than 1‰) into roof gutters. Fig. 1 presents a schematic of typical extensive green roof layers and design characteristics, discussed in the following paragraphs.

Green roof media and vegetation properties differ from similar systems on the ground. Media composition is engineered to contain a majority of porous aggregate, less than 25% organic material, and a small percentage of fines, lightweight additives, and minerals [46]. The bulk (dry) density of the media, ranging from 0.34 to 1.31 g cm⁻³ [25,28,47,48], is thus low compared to natural soils [49]. Vegetation that survives in thin substrates with limited nutrients and water availability are typically used [23–27], including those that are drought and heat tolerant, with low biomass, minimal height (less than 20 cm), and short roots [5,26]. Green roofs are intended to be fully covered in vegetation (a fractional vegetation coverage (ρ) of 100%); however, in reality, 80% coverage is considered high because roofs are rarely irrigated or
fertilized to increase coverage. These design properties are ideal to minimize structural loading and maintenance; however, they could also limit the benefits achievable by the green roof, as discussed in Section 4.

2.2. Description of co-benefits and associated physical processes

Before assessing the influence of the design properties on the achievable benefits, quantifiable performance metrics must be designated that relate these benefits to the physical processes and properties governing them. This section describes the four co-benefits discussed in this study (stormwater attenuation, heat mitigation, solar panel output improvement, and building thermal performance), which metrics are useful to characterize them, and how they relate to the water and energy balance. Defined in Table 1 and mathematically formulated in Section 3, these co-benefits are: stormwater detention and infiltrability, heat mitigation, and building thermal performance.

Table 1 summarizes definitions of the important physical processes and properties related to the green roof and their associated equations. Which processes and properties influence the different co-benefits (and their evaluation metrics).

2.2.1. Stormwater attenuation and retention

Urban stormwater is rainwater (and melted snow) that collects on impervious surfaces and usually runs off into collection systems. The frequency of runoff exceeds the inflow capacity of the collection system, water can back up into streets and cause localized flooding or, in cities with combined sewers, trigger combined sewer overflows (CSOs) of untreated wastewater into surface waters [50].

Green roofs can diminish these problems by attenuating the magnitude and timing of the maximum runoff flowrate per storm event (referred to as peak discharge). This is accomplished through temporary stormwater detention in soil or on leaves [22,51], which is influenced by the discharge rate ($q_d$) from the engineered media and the volumetric water content (VMC) of the media (Table 2). Detention can be evaluated with metrics related to changes in magnitude or timing of discharge [51], including the lag time ($t_{lag}$). Usually calculated in minutes [52], lag time is the time between the start of a rainstorm ($t_p$) and the start of discharge ($t_d$) from the bottom layer (Eqn. 1). Detention is improved with a longer lag time or slower discharge.

\[ t_{lag} = t_d - t_p \]  

In addition to peak attenuation through detention, green roofs can also reduce the total runoff entering the sewer [9]. Volume reductions are sometimes used to calculate water quality targets [53,54]; however, attenuation is the more important stormwater service because it diminishes flooding and CSOs, whereas reducing total stormwater has a minimal influence on treatment plant operation. On the other hand, retention of water inside the engineered media is important to ensure plant survival during dry periods [55]. Retention is quantified in percent as the relative retention (RET; Eqn. 2). RET is the volume of water retained ($V_r$) in the soil after losses over a period of time ($t$), relative to the volume of water that entered the soil during this period ($V_{in}$), usually as precipitation ($p$). As shown in Table 2, $V_r$ depends on VMC and the water lost through discharge ($q_d$) and evapotranspiration (ET). This relationship is defined mathematically in Section 3.1.

\[ RET = \frac{V_r}{V_{in}} \]  

Green roofs have been shown to annually retain an average of 55–88% of runoff [56]; whereas retention per rainfall event varies more widely, from 15 to 72% for median event based retention [57]. Median peak discharge attenuation ranges from 43 to more than 90% [58,59]. However, event based performance metrics depend on the magnitude of the rainstorm [60] (see Section 3.5) and the green roof design properties (see Section 4.1).
2.2.2. Urban heat mitigation

Urban heat mitigation refers to strategies that aim to reduce the negative impacts of urban heat, especially those that lower temperatures at the hottest time of day [61]. Green roofs can help mitigate urban heat [10,62] because they reduce the sensible heat flux ($Q_s$) above the roof through increases in evapotranspiration and alterations in the radiation flux ($R_n$) (as shown in Table 2).

The sensible heat flux can be used as an evaluation index for urban heat mitigation, as defined by Takebayashi and Moriyama (2007) [63] and Sailor (2008) [64]. Scherba et al. (2011) went further to suggest that the peak sensible heat flux ($H_2$) (W m$^{-2}$) and the total daily sensible heat flux (MJ m$^{-2}$ day$^{-1}$) are also relevant [65] because they influence the maximum daytime temperature and nighttime cooling, respectively. The peak sensible heat flux ($H_2$) is presented in Table 2 as an evaluation metric for urban heat mitigation; however, quantifying reductions in sensible heat flux are not straightforward because direct measurements are difficult in practice [66] and modeling is complex. Urban scale microclimate models [67–70] are needed to link the sensible heat from the green roof directly to urban heat mitigation. Some experimental studies instead use the surface or canopy air temperature as a proxy to evaluate urban cooling from green roofs [30,44,71–75] or try to quantify reductions in space cooling [76]. However, none of these proxies are satisfactory because building scale factors are difficult to experimentally link to the urban scale without modeling the microclimate [67–69,77].

Green roofs can reduce peak surface temperatures by as much as 25 °C relative to conventional roofs [29,78,79], whereas air temperatures above the roof may only change by one degree or less [80,81]. Scherba et al. (2011) [65] found that a green roof has the potential to reduce the total daily sensible heat flux by 52% compared to a black roof, even though white roofs reduced this flux by 30% more than green roofs. However, reductions in heat will vary depending on climate, soil moisture, diurnal patterns, and urban canyon configuration (walls, roads, etc.). Reductions can be small [71] or even exhibit a negative penalty [25,71,82].

2.2.3. Solar panel output improvement

Solar photovoltaic (PV) panels produce distributed, renewable energy by converting solar radiation into electricity. Solar panel power output depends on the available solar radiation and the conversion efficiency, which is reduced as temperatures rise above the reference temperature (usually 25 °C) by approximately 0.45% per 1 °C for crystalline silicon panels [83,84]. Shown in Table 2, green roofs can improve conversion efficiency by keeping operating temperatures low through their ability to decrease the sensible heat (by increasing ET) and LW radiation absorbed by the panels (by decreasing surface temperature) [12,85,86]. Depending on the green roof configuration, outgoing LW radiation could also increase, which could be converted to heat on the panel, decreasing panel efficiency. However, some PV panels can convert LW radiation to electricity, which would increase solar panel output. Light colored green roof vegetation and substrate may also reflect SW radiation back into the atmosphere, which can increase the solar radiation available for panels to convert to electricity in some cases, including when they are vertically mounted [87].

Various performance metrics have been used to quantify the effect of green roofs on solar panel output, including comparisons of: instantaneous power output over time [12], the average energy yield for a fixed time period [88], and the specific energy yield (Y), which is the energy per unit peak power for a fixed time period [86]. The latter, shown in Eqn. (3) and Table 2, is useful for comparison of PV systems of different sizes and nominal efficiency ratings on vegetated and non-vegetated roofs because it describes the amount of energy produced ($E_o$) relative to the maximum capacity of the system under standard conditions ($P_{peak}$), irrespective of panel surface area.

$$Y = \frac{E_o}{P_{peak}}$$

(3)

Compared to traditional roofs, experimental and modeling results show that green roofs could increase annual PV electricity yield from 0.5% to 8.5% [12,37,89–93]; however, results vary depending on the climate and the green roof design properties. In cooler climates, the increases may not be as significant [89].

2.2.4. Building thermal performance

Efforts aimed at increasing the ability of buildings to maintain indoor temperature, despite external weather fluctuations, is a concept referred to as improving the thermal performance of a building [94–96]. Green roofs increase building thermal performance in summer by altering the radiation flux (through shading and reflectivity) and increasing evapotranspiration (shown in Table 2). Green roofs also improve it throughout the year by adding insulation, which can be approximated as the thermal resistance (R-value) (shown in Table 2) and by increasing thermal mass (approximated by the heat capacity), which decreases the rate the roof will heat up and cool, stabilizing building temperatures [11,29,97]. The combination of the available energy and thermal resistance controls the amount of heat flowing into and out of the building, which can save energy in both warm and cool months.

To quantify the influence of the green roof on building thermal performance, a few studies consider the conductive heat flux ($Q_c$) from the green roof to the building [98–105], which could be used as an evaluation metric. To quantify building energy load (in MJ or kWh), other metrics are used, such as the monthly energy usage difference between a building with a conventional roof and one with a green roof [64] or the ratio between the two, referred to as the Dynamic Benefit of Green Roofs (DBGFR) [104]. In this case, the conductive flux is used as input to whole building energy simulation models, such as EnergyPlus™, or in urban scale climate models that represent the built environment (e.g., Ref. [67,77]).

Experimental and modeling results show that green roofs can reduce annual building electricity consumption by as much as 4% [64,81,104,105]; however, this can be seasonally higher or lower depending on the
climate and green roof design properties [106–108]. Due to the complex energy balance (described in the next section), a green roof will not always lead to building energy savings [104].

3. Conceptual water and energy balance in a green roof

In this section, we show how the processes listed in Table 2 are linked to each other through the water and energy balances, increasing the complexity of understanding green roof co-benefits. Water and energy cycle in and out of the green roof in three main ways: (i) as water interactions within the substrate layer, (ii) as a release of water, heat and radiation at the green roof surface, and (iii) as heat stored and transferred through the substrate.

3.1. Substrate-water interactions

Generalized in Eqn. (4) and shown in Fig. 2, water entering the green roof as precipitation (p) is equal to the change in water stored in the substrate (ΔS) plus water leaving as ET, surface runoff (q_r), or vertical drainage (q_d). Not all processes happen simultaneously, however. Discharge takes place primarily during rain events, whereas ET is released in between these events, decreasing the amount of water stored [109,110]. Furthermore, surface runoff is usually negligible because water infiltrates quickly into the highly porous media [48,111].

\[ p = \text{ET} + q_r + q_d + \Delta S \]  

When water rapidly enters the green roof, the substrate media is likely unsaturated and the water in non-steady state, meaning that all pores are not saturated before drainage occurs [48,111,112]. Unsaturated flow through a vertical soil column (1-D) can be described using the Darcy-Buckingham Law (Eqn. (5)) [67,113] or Richard’s equation under transient flow [114] (see Appendix A.3.).

\[ q_s = K \left( \frac{\psi_m}{\partial z} + 1 \right) \]  

Shown in Fig. 2, vertical drainage is a function of the unsaturated hydraulic conductivity (K) and the change in soil matric potential (\( \psi_m \)) with respect to the change in depth (z). K, which describes the permeability, or how well water flows through connected pore space (see Appendix A.4.), is a function of the hydraulic conductivity at saturation (K_s), related to soil properties [115], and the soil moisture (\( \theta \)) or the volumetric water content (VMC; defined in Table 1 and Appendix A.1.). Soil matric potential, which describes the ability of soil to attract water using cohesion and surface tension, increases as \( \theta \) decreases [117] and also relates to soil properties.

The maximum amount of water that can be stored in the substrate before drainage by gravity is referred to as the maximum water holding capacity (WHC_{max}) or the water content at field capacity (\( \theta_{fc} \)) [118]. At a certain point, referred to as the wilting point (\( \theta_{wp} \)), plants can no longer uptake water due to high matric potential [119]. The maximum retention capacity (S_{max}) (Eqn. (6)) is the difference between the water content at field capacity and wilting point.

\[ S_{max} = \theta_{fc} - \theta_{wp} \]  

3.2. Water and heat released at the surface

The water balance is linked to the energy balance through ET, which is converted to an energy flux (called latent heat, Q_e) by multiplying it by the latent heat of vaporization (\( \lambda \)) [39,120]. ET (Eqn. (7) [121]) is a dynamic process governed by the vapor pressure deficit (VPD) between the surface and air (\( e_s - e_a \)), as well as, the resistance to water loss from the surface (\( r_s \)) and into the air (\( r_{ma} \)). The VPD, a function of ambient air temperature, \( T_a \), is the amount of moisture that can be added to the air before saturation [39,99,122]. For practical reasons, Eqn. (7) is often replaced by the Penman-Monteith (P-M) reference equation [120], discussed in Appendix A.5.

\[ \Delta ET = Q_e - \frac{\rho_a C_p}{T_s r_{ma} + T_a} (e_s - e_a) \]  

where variables are defined in the nomenclature.

The surface resistance \( r_s \) (Eqn. (A7) Appendix A.6, [120]), represents the resistance due to physiological properties of the soil and vegetation, including the stomatal resistance (\( r_t \)), the force opposing the release of water vapor through leaf stomata (pores), and the leaf area index (LAI), the projected leaf area per unit ground area (m^2/m^2) [39]. Both of these variables can be influenced by the choice of vegetation, while \( r_t \) also changes over time as a particular plant responds to changes in environmental conditions, including solar radiation, vapor pressure deficit, soil water content, air temperature [123] and even soil type [74]. The aerodynamic resistance to vapor transfer (\( r_{ma} \); Eqn. (A8) Appendix A.7.), is related to atmospheric turbulence (e.g., friction from air flowing over the top of the vegetation) [124]. It is a function of surface roughness (related to plant height), wind speed (u) and atmospheric stability [78,120,125] (see details in Appendix A.7.).

The available energy at the surface is partitioned between the latent and sensible heat [126]. The sensible heat flux (Q_h; Eqn. (8) [97,127]), is a function of the temperature differential between the surface and the air, as well as the aerodynamic resistance to heat transfer (\( r_a \)) which is related to \( r_{ma} \), but describes resistance to heat instead of vapor. The two terms are often interchangeable since differences are minimal [125], and are sometimes referred to collectively as aerodynamic resistance (\( r_a \)) to the transfer of heat and vapor (as in Ref. [124]; see Appendix A.7.).

\[ Q_h = \frac{\rho_a C_p}{T_s - T_a} \]  

3.3. Radiation interactions at the surface

ET and sensible heat are part of a larger energy balance, generalized for green roofs in Eqn. (9) [125,128]. Net radiation (\( R_{an} \)), the difference between incoming (\( R_{in} \)) and outgoing (\( R_{out} \)) radiation, is equal to convective heat released into the air as latent (Q_e) or sensible heat (Q_h), conductive heat (Q_c) transferred through solids, or energy transiently stored by the substrate or vegetation (\( \Delta Q_s \)).
\[ R_n = R_{in} - R_{out} = Q_e + Q_H + Q_G + \Delta Q_s \quad (9) \]

Outgoing radiation (Eqn. 10) is the sum of outgoing short (SW_{out}) and longwave (LW_{out}) radiation. SW_{out}, governed by the surface albedo (\( \alpha \)), is the fraction of incoming short-wave radiation (SW_{in}) that is reflected from the surface. Often assumed constant, albedo changes depending on the substrate moisture content [129], fractional vegetation coverage (\( \eta \)), and vegetation height [97,130]. LW_{out} from the green roof to the atmosphere is a function of surface temperature (\( T_s \)) to the fourth power, surface emissivity (\( \varepsilon \)), as well as, incoming LW radiation [99].

\[ R_{out} = SW_{out} + LW_{out} = \alpha SW_{in} + \varepsilon \sigma T_s^4 + (1 - \varepsilon) LW_{in} \quad (10) \]

SW and LW radiation fluxes within plant canopies are more complex. They can be represented using the radiation fluxes at the top of the canopy and the transmittance (\( \tau \)) through the plant canopy (see Fig. 3). Transmittance, which quantifies how much radiation is scattered by the vegetation [97], relates to the vegetation properties, including vegetation coverage (\( \eta \)), LAI and leaf angle distribution, as discussed in Appendix A.8. [97,131,132].

3.4. Heat stored and transferred through the substrate

Just as water is stored in the substrate, energy can also be stored in green roofs, although this may be negligible in thin soils [128] and vegetation. Thermal storage (\( \Delta Q_s \); Eqn. 11) [125,128]), the rate of change in heat content of the roof per unit volume, is represented as the rate of change in roof temperature (\( dT/dt \)) times the heat capacity (\( C_s \), with units J m\(^3\) K\(^{-1}\)), which is defined as the amount of heat (J) needed to raise a unit volume (m\(^3\)) by 1°C (K). Specifically for substrate, the heat capacity (\( C_s \)) depends on the relative fraction of solid particles, air, and water and the thermal properties of each material [125].

\[ \Delta Q_s = C_s \frac{dT}{dt} \quad (11) \]

Heat flowing through the substrate is referred to as the conductive heat flux (\( Q_G \); see Fig. 3). Shown in Eqn. (12) [99,133], the magnitude of the flux is proportional to the temperature differential between two depths that define a layer, as well as, the thermal conductivity (\( \lambda \)) of this layer. As with water, heat entering the green roof surface is not equal to heat leaving from the subsurface. Thus, the depths and temperatures to consider will change depending on whether the top or bottom of the green roof is evaluated (see Appendix A.9.).

\[ Q_G = \lambda \frac{dT}{dz} \quad (12) \]

Thermal conductivity (\( \lambda \)) the rate at which heat is transferred across a material, is the inverse of thermal resistance (R-value), which is related to insulation (see Section 2.2.4). It varies over time with the depth of substrate and moisture content [99,125] and is a function of substrate porosity (density) and composition, and thermal capacity of substrate particles [134] (see Appendix A.9. for specific equations).

3.5. Intersection of surface, sub-surface, and boundary conditions

Fig. 4 summarizes the relationships between the exogenous weather variables known as boundary conditions (white boxes at top), the water (blue circles) and energy (black circles) balance terms (Eqn. (4) and Eqn. (9), respectively) and the parameters that dictate them, which are related to green roof properties for vegetation (green squares) and substrate (brown squares).

From Fig. 4, we see that the local climate patterns (i.e., the boundary conditions: rainfall, wind, vapor pressure deficit, air temperature, and incoming radiation) influence the co-benefits both directly and...
indirectly. Of particular importance is rainfall intensity, which directly influences soil moisture (i.e., retention of stormwater) and discharge rate \[52,60,135,136\]. The magnitude of the rain storm dictates the percent of rainfall that is retained and the time between storms dictates the antecedent moisture conditions (AMC). Based on an analysis in three Canadian cities, small events (<3 mm) were fully retained, large events (>15 mm) were not, and retention of medium storms (3–15 mm) was dependent on the AMC \[60\]. When antecedent soil moisture is high and infiltration capacity is reduced, surface runoff (or ponding) could also increase \[137\].

In addition to stormwater discharge, soil moisture also influences many of the other processes and parameters, including thermal conductivity, which increases with moisture content \[108,138,139\] (see Section 4.5). Evapotranspiration also depends on VMC. ET is usually low when VMC is low, high when it is high, and is approximately linear to increases in moisture in between \[140\] (see Section 4.3). When ET is not limited by soil moisture, like in a wet, temperate climate, it uses 70%–80% of energy received from solar radiation, leaving only 16–30% for sensible heat, and 3–15% for conductive heat through the green roof \[99\]. However, in drier climates, sensible heat can account for nearly 70% of energy, while ET only accounts for 25%. Thus, the sensible heat is indirectly linked to soil moisture through its dependence on ET. Some studies have found that irrigating the green roof during times of low rainfall increases ET \[25,110\], which would also reduce sensible heat.

Processes relying on ET for cooling, however, are dependent on the relative humidity (linked to VPD), which determines the amount of water the air can accept. Irrigation is more effective in drier and more temperate climates, and less so in more humid and tropical climates where air is nearly saturated \[141\]. The following recommendations are provided for a dry or temperate climate where ET could be a key driver for cooling and where soil moisture could influence retention for medium sized precipitation storms.

4. Altering processes through changes in green roof design parameters

In the previous section, we presented how the processes identified in Table 2 are linked to each other and to the substrate and vegetation parameters of a green roof. In this section, we review the literature on each process to describe how green roof design properties can influence co-benefits achieved by the green roof. Fig. 5 presents the 13 design properties discussed in this section by category (left most column): irrigation, substrate, vegetation, and surface, and (a) how an increase in these properties would influence the physical processes, or the direction of change needed in these properties to (b) maximize the co-benefits, or (c) minimize the constraints.

4.1. Discharge rate

As shown in Fig. 5, the discharge rate primarily influences stormwater detention. Decreasing the discharge rate will improve detention; however, the rate must still be high enough to avoid water ponding on the surface of the green roof \[55\]. As discussed in Section 3.5, discharge increases with higher precipitation intensity and antecedent soil moisture. Discharge can be decreased by changing the substrate depth and composition, the properties of other green roof layers \[51\], and in some cases, vegetation coverage. For example, Yio et al. (2013) showed that discharge decreases as substrate depth increases, but found that the relationship was not linear \[142\]. Peak discharge attenuation has been shown to be higher on roofs with vegetation than bare soil \[57\], although it remains unclear whether the type of vegetation (and the leaf area) can also influence discharge.

Discharge can be also decreased by altering the physical properties of the substrate, which influence the unsaturated hydraulic conductivity (K) and the matric potential (\(\psi_m\)) (see Eqn. (5)). For example, Bollman et al. (2019) found that peat moss detained more water than other substrates that had a higher mean grain size (e.g., lower density) and
higher hydraulic conductivity than peat moss. However, a lower hydraulic conductivity may not guarantee higher detention. A different sample of sand that had the lowest hydraulic conductivity, but higher density than the peat moss, released more water after a minute [55]. The material’s surface tension, or capillary pressure, which was not evaluated in this study, also plays a role, although this characteristic is difficult to attribute to a particular soil.

Theoretically, the capacity of a medium to convey water (related to K) depends on the pore size distribution (abundance and size of soil particles), connectivity (how many flow paths), and tortuosity (number of turns per path) [143,144]. Larger pores drain water faster, but the presence of smaller pores alongside larger ones also slows water down. For instance, several studies found that increasing the amount of organic matter (even by 5%), which increases the number of fine particles and decreases K, can considerably reduce the discharge rate [55,142]. The microporosity and particle texture also plays a role in water drainage. This is why sand (round particles), which has a lower hydraulic conductivity than other common green roof media (e.g., perlite or tuff), has been shown to contain less water at the same matric potential than other substrates with higher K and more jagged particles [55,143,145]. The relationship between unsaturated flow and substrate composition is complex and the literature is far from exhaustive on this topic, especially for green roof media, which behaves differently from natural soils.

Ultimately, to reduce the discharge rate and improve detention, substrate depth, organic content, particle roughness, and vegetation coverage should be increased when possible, while antecedent soil moisture should be decreased (Fig. 5 – first column) by increasing ET (see Section 4.3) or limiting irrigation.

4.2. Volumetric water content

As discussed in Section 3, the substrate water content can alter each of the energy and water balance processes (to varying degrees) and thus influences all of the co-benefits. However, depending on the benefit, it may be preferential to increase or decrease soil moisture (see Fig. 5). This section discusses ways to retain more moisture in the substrate after a rainfall or irrigation event, thus increasing the time it takes the soil to reach the wilting point. Although decreasing ET from plants would technically increase soil moisture, this aspect is excluded from this discussion, as is depression storage on leaves.

VMC after rainfall (or irrigation) depends on the maximum retention capacity \(S_{\text{max}}\) (Eqn. (6)), substrate depth and substrate properties. Substrate depth is shown to be significantly positively correlated to moisture retention [22], although there is an inflection point where additional increases in substrate depth will only marginally change the retention capacity. For instance, Metselaar (2012) found that increasing substrate depth from 5 to 15 cm increased the retention fraction by 10%, yet beyond 60 cm, increases in retention were minimal [146]. This is
promising because larger moisture retention could be achieved with minimal increases in substrate depth.

As with discharge, the ability of substrate to retain moisture also depends on organic content and particle distribution, however, the relationship is not straightforward. Nektarios et al. [147] observed higher water content in loamy media during drought than in media without organics [111]. However, Bollman et al. (2019) found the highest water content after 14 days in perlite media, which had a lower percentage of fine particles (<2 mm) than other materials, including peat moss and sand [55]. Graceson et al. (2013) did not find a significant difference in short-term retention in substrates with varying percentages of fines (2.5%-57%) [148]. As shown in Fig. 5, it is still unclear how changes in particle distribution (ratio of small particles) influence the retention of moisture. It is likely also linked to particle texture and thus capillary forces of each media type; however, this has not been evaluated.

By mixing different substrate materials or adding additional layers to the green roof, moisture content can be increased without considerably decreasing detention. For example, Bollman et al. (2019) mixed 80% perlite (highest 14-day moisture content) with 20% peat moss (highest short-term detention) and found that the percent of water retained doubled while detention only decreased by one third [55]. Moreover, Farrell, Ang, and Rayner (2013) found that adding water retaining materials to green roof soils, such as silicate granules, improved water retention by as much as 9.4% [149]. Finally, another approach could be to place an engineered water retention layer below the substrate, similar to those offered by Nophadrain [39], in order to retain moisture for plants. Overall, soil moisture is retained longer by increasing substrate depth and the percentage of organics and fines (although not in every case).

4.3. Evapotranspiration

As shown in Fig. 5, increasing ET would improve all of the co-benefits. Apart from ensuring there is ample soil moisture for ET to take place, one of the primary ways to increase ET is to decrease the resistance to water loss from the surface to the air (see Eqn. (7)). Aerodynamic resistance (r_a, equation shown in Appendix A.7.) could be lowered by increasing surface roughness, which could be accomplished by increasing plant height (or height variation). Nagase and Dunnett (2012) [28] found that for every 1 cm increase in plant height, cumulative runoff volume reduced by 0.4%. Since substrate characteristics did not change, this likely means that ET increased with plant height; however, it could also be due to increased interception. This relationship was not linear (R² = 0.465), implying that there are other factors at play. Most notably, these findings could also be due to changes in ET through the surface resistance term, which is related to the stomatal resistance (r_s) and leaf area index (LAI) of the vegetation (shown in Eqn. (A7)).

Surface resistance decreases as LAI increases, which is one of the most important plant characteristics related to ET [39], because there is more surface area available to release water. It is difficult to decouple LAI from stomatal resistance in terms of ET, especially since LAI changes seasonally, while stomatal resistance changes daily. However, the role of LAI is non negligible. One agricultural study showed the ET rate of two crops diverged at the same point in the season when LAI of one crop started to decline while the other continued to increase [150]. Moreover, when sparse vegetation is compared to dense (i.e., more surface area of leaves), ET is more intense in the former case [151] and less stormwater leaves the roof [152]. These increases in ET could also be due to differences in structural complexity (e.g., variation in plant height, branching, and leafiness); however, one study found that vegetation structure did not significantly affect green roof cooling [153].

Surface resistance also decreases with lower stomatal resistance (r_s), which varies among plant species [154]. Stomatal resistance is lowest in C4 plants, a vegetation group consisting mainly of grasses and herbs, with r_s values of ~50–60 s m⁻¹ for these species [155,156]. This is one of the reasons why grasses have been shown to be more effective at reducing stormwater (and thus releasing water through ET) than succulent and forbs species [28,155], which have higher stomatal resistance. Crassulacean acid metabolism (CAM) plants (mostly succulents) have an r_s ranging from 170 [156] to 1000 s/m [157]. Of particular importance is the relationship between stomatal resistance and VMC because a lack of moisture limits stomatal opening and ET, but ample moisture increases them [39,74,99,101,110,138]. However, an exception to this pattern would occur if deep-rooted plants access moisture at lower substrate depths. In this case, ET could still increase even as the top of the soil decreases in moisture content.

Ensuring soil remains moist (i.e., through irrigation) is especially important for survival of taller plant species with lower stomatal resistance (like grasses). These plants will continue to release water even when soil moisture decreases and will wilt once soil moisture gets too low. It follows logically that some studies have found that irrigating the green roof during times of low rainfall also increases ET [25,110] and reduces air temperatures [153]. As an alternative to increasing irrigation, substrate depth and plant root depth could be increased so that plants could access moisture at lower soil levels, even when the soil surface is dry.

Finally, it may be possible to increase ET by reducing vegetation coverage, thus excluding the resistance linked to vegetation. Several field studies have shown that bare (or sparsely covered) substrate loses more water to ET than well covered green roofs [25,158,159]; although this is often only the case when soil is moist after irrigation. Over dry soil before irrigation, Cousts et al. (2013) found that ET was lower and sensible heat higher over soil than vegetation [25]. Stovin et al. (2015) suggest that ET is only increased by plants as soil moisture declines [57]. However, some studies have also shown that ET is higher from vegetated roofs than from bare soil [57,110,160] even under well-watered conditions, as in a greenhouse experiment conducted by Voyde et al. (2013) [110]. Many factors may play a role in whether soil or vegetation contribute more to latent heat, including differences in shading, albedo, substrate temperature and moisture, stomatal resistance [25,135,155], root depth, and atmospheric conditions.

While it is still unclear whether vegetation encourages or suppresses ET, it is clear that without it, a green roof would lose the ecological function to promote biodiversity as well as the shading function that decreases energy sent to the building (see Section 4.4). Moreover, a dry green roof with little to no vegetation could increase heat at the surface due to low thermal admittance (the square root of the product of thermal conductivity and heat capacity) [125]. Thus, the preferred way to increase ET and surface cooling could be to select vegetation with low surface resistance or to mix these plants with higher surface resistance vegetation (e.g., Sedums) so more water is available to the plants that need it [24,153]. Overall, as shown in Fig. 5, when plants are present, ET increases with lower resistance (e.g., taller plants, higher LAI) and higher moisture availability (e.g., increasing irrigation or root depth). Many of these species grow in substrate depths of 15 cm or less [21].

4.4. Outgoing radiation and shading

Limiting the incoming radiation below the vegetation canopy (i.e., absorbed radiation) will positively influence all of the heat related benefits. As shown in Fig. 5, absorbed radiation is decreased if more shortwave radiation is sent back to the atmosphere by altering the albedo (Eqn. (10)) and if radiation is blocked from reaching the soil surface through shading. Green roof surfaces below dense canopies (with high shading) absorb as little as 2% of net radiation, while surfaces below sparse canopies absorb as much as 30% of Ru [154]. It may also be possible to release more absorbed radiation (reducing stored energy) by increasing surface emissivity.

Albedo is increased by selecting light or silver colored plant species, including: many grasses (albedo ranging from 0.25 to 0.30 [161]), light colored Sedums such as Sedum tomentosum (0.23) or sexangulare (0.22)
Building thermal performance is improved by decreasing the downward conductive heat from the bottom of the green roof. As shown in Eqn. (12), heat transfer in substrate is decreased with lower thermal conductivity, $\lambda$, which means that more energy is stored in the substrate rather than conducted away. Thermal conductivity depends on moisture content (VMC), as well as, the substrate density and the thermal capacity [134] of substrate particles (see Appendix A.9.). Specifically, heat transfer has been shown to increase in higher density substrates [26], meaning that lower porosity soils with high field capacity [134] and a lower percentage of small particles are preferred to reduce conduction and improve building thermal performance (see Fig. 5). However, in this case, surface temperatures may increase. Due to lower thermal diffusivity, low density soils (e.g., peat) diffuse heat slower than higher density soils, meaning more heat is available at the surface [125] and higher organic content tends to increase surface cooling [153].

As discussed in Section 3.5, conductive heat increases through wet substrates [108,136,139]. Specifically, thermal conductivity of saturated soils has been shown to be double that of dry soils [129] because air is a better insulator than water [11]. Dry, highly porous substrates will be most effective at decreasing the conductive heat flux through the green roof [134]. However, this does not account for the fact that heat capacity of saturated soil is higher than for dry soils [125], thus energy will be stored longer inside moist substrate with more energy released at night (usually at the surface). Lower soil moisture also decreases ET [99, 125], which would increase the surface temperature and sensible heat flux. Contributions from ET and energy stored in the soil could be why Sailor (2008) found that irrigating during summer could decrease monthly building energy consumption, although marginally. One way to increase the insulating properties of the green roof without reducing moisture could be to add glass beads filled with air into the substrate [131].

Heat released below the green roof also depends on the substrate depth [99,125]. Mathematically, the energy released over time is related to the change in temperature per change in depth (see Eqn. (12)) and the energy storage (see Eqn. (11)). Deeper substrates have been attributed to lower heat gains and losses, a higher degree of insulation [106,131], and reduced building energy consumption [108]. However, improvements in building energy consumption due to increases in depth are smaller in moist substrates [108]. Sailor (2008) found that the substrate depth was a larger contributor to thermal performance than the fractional vegetation coverage (related to shading, transmissivity) [129], although Taboares-Velasco and Srebric (2012) found that the LAI had a larger influence than the substrate depth on the conductive heat flux through the green roof [99]. The difference may depend on the magnitude of feasible changes to design parameters. For example, increasing the LAI by 2 or 3 units may be easier than increasing the substrate depth by more than 10 cm, as was suggested by Sailor (2008). Ultimately, the relative importance of each also depends on local climate, season, and the baseline comparison values.

The ability of a green roof to reduce heat flows into the building also depends on the insulation (e.g., wool or fiber glass) that lies between the green roof and building. Wong et al. (2003) found that a green roof on an uninsulated building decreased energy consumption for cooling by 15%, but a green roof over an insulated roof decreased consumption by less than 2% [108]. Thicker insulation layers dampen the benefit of a green roof to reduce energy flows into the building [108,162], especially in winter. In summer, Vera et al. (2017) found that ET and shading from the vegetation could be more effective at reducing heat fluxes into the building than increasing roof insulation [170]. Shown in Fig. 5, to reduce conduction and improve building thermal performance, one should increase its insulation power (by increasing substrate depth, decreasing small particles and decreasing soil moisture) and reduce available radiation (see Section 4.4).

4.7. Trade-offs and synergies between co-benefits and constraints

Fig. 5c summarizes how the green roof design properties influence all the co-benefits and constraints (which include structural loading, maintenance, and cost). The constraints are minimized primarily by reducing irrigation, substrate depth, substrate density, and plant height. Relaxing these constraints could improve the achievable benefits or lead to trade-offs. For instance, deeper substrates (e.g., ~15 cm) with more organics detain more water, reduce surface heat, and allow for a wider variety of plants to grow, including deeper rooted grasses and forbs
species with higher ET and cooling [25]. However, increasing substrate density could increase conductive heat and reduce building thermal performance. There are other design properties that could be altered to maximize co-benefits without trade-offs, including substrate particle roughness or engineered substrate additives, leaf area index, and surface properties like albedo and emissivity. Increasing leaf area and vegetation coverage can considerably cool rooftop temperatures and increase building thermal performance [6,9,36,39]. Using performance-based modeling to determine the optimal combinations of design properties is a challenging, yet crucial step towards boosting synergies and managing trade-offs.

Performance-based modeling is also needed to evaluate trade-offs and synergies related to irrigation systems, which increase cost and loading, remain unused when rainfall is sufficient, and may increase demand for drinking water during periods of water stress [40]. Dry soil could also increase stormwater detention (more room to store water) and energy savings (air insulates better than water). However, irrigation may be needed during hot, dry spells (expected to increase under climate change [171,172]) for survival of plant species with low stomatal resistance that encourage ET (and cooling). These factors are compounded by the fact the irrigation water could be supplied from harvested stormwater or grey water and could also be used to clean solar panels. Ultimately, the decision to irrigate depends on these trade-offs as well as the importance of cooling relative to the other benefits, especially in a more extreme climate.

As integrated solar panel green roof systems become more established, performance-based modeling for green roofs will become more critical to balance synergies and trade-offs in design properties with other co-benefits, including the fact that PV modules can decrease surface albedo [173]. When solar panels are present, the choice of vegetation and surface properties is more critical, yet more constrained [163]. For instance, vegetation should be short in order to avoid shading the panels from above [21] and large leafed, silvery plants that increase albedo, shade, and cool the rooftop [30] should be prioritized since they have been shown to increase electricity production [86]. Finally, adding solar panels to the roof also increases shading on the roof [173], which would improve building thermal performance. As communities continue to expand rooftop solar energy, these interactions will be important to examine in future performance-based design models.

5. Outlook and future research needs

Performance-based design models for green roofs are needed in order to optimize green roof design parameters based on multiple objectives, including environmental co-benefits and structural and maintenance constraints. Given the trade-offs discussed previously, the optimal balance of design properties will depend on the importance of each benefit (or constraint) to stakeholders, which can be investigated using decision analysis (e.g., Ref. [174,175]). A decision analysis model first requires a performance analysis that uses simulation models to capture the relationships between co-benefits and design properties. This study generalized the complex physical concepts to provide the foundation for this performance analysis; however, more work is needed to use this foundation to build a comprehensive performance-based design model. This requires the integration of simulation models and solvers [35,64,176–179] that can portray complex relationships into a simplified framework so the performance analysis can be linked to optimization and/or decision analysis. Consortia is needed among researchers conducting green roof simulation modeling in different disciplines, as well as, with those working on multi-objective decision making.

In addition to model integration across disciplines, more research is needed within disciplines to standardize modeling parameters for different green roof designs and link these parameters mathematically to the performance objectives. For instance, combining various materials into the substrate, as suggested in this study, would change the thermal and hydraulic properties of the green roof. The parameters of these substrate mixtures, however, are not well known. Coefficients that depict transpiration (e.g., stomatal resistance) are limited for many landscape plants, as are canopy values for combinations of plant species. Laboratory and field studies are required to classify and standardize these properties. In order for practitioners to use this information, a universal database where these values can be reported is also vital. Finally, additional research is needed in some cases to show how certain design properties influence the physical processes. For instance, it is still unclear how LAI and substrate organic content relate to discharge timing or how solar panels above green roofs affect air and building temperatures. As practitioners gather more information about system interactions, more intricate green roof designs can be evaluated using performance-based design.

While this study only focused on the four co-benefits linked to the energy and water balance, future performance-based design models should also consider other green roof co-benefits, such as biodiversity enhancement [13,14], carbon dioxide sequestration [15], air pollution abatement [16,17], and improvements to urban livability. For instance, a minimum soil depth could be instrumental for invertebrates to hibernate in substrate over winter months, and pollinating species may be more prone to certain flowering plants. Moreover, carbon dioxide sequestration is increased as stomatal resistance is decreased (the amount water vapor exiting pores is proportional to CO2 entering), which could be another reason to select plant species with low stomatal resistance. Interdisciplinary collaborations among green roof researchers are needed to incorporate multiple perspectives.

Declaration of competing interest

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Appendix A. Supplementary data

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References

[1] J. Sheffield, E.F. Wood, Projected changes in drought occurrence under future global warming from multi-model, multi-scenario, IPCC AR4 simulations, Clim. Dynam. 31 (2008) 79–105.
[2] R.P. Allan, B.J. Soden, Atmospheric warming and the amplification of precipitation extremes, Science 321 (2008) 1481, https://doi.org/10.1126/science.1160787.
[3] T.A. Larsen, S. Hoffmann, C. Lüthi, B. Truffer, M. Maurer, Emerging solutions to the water challenges of an urbanizing world, Science 352 (2016) 928, https://doi.org/10.1126/science.aad8641.
[4] H. Eggermont, E. Balian, J.M.N. Azevedo, V. Reumer, T. Brodin, J. Claudet, B. Fady, M. Grube, H. Keune, P. Lamarque, Nature-based solutions: new influence for environmental management and research in Europe, GAIA-Ecol. Perspect. Sci. Soc. 24 (2015) 243–248.
[5] K. Vijayaraghavan, Green roofs: a critical review on the role of components, benefits, limitations and trends, Renew. Sustain. Energy Rev. 57 (2016) 740–752.
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S. Vera, C. Pinto, P.C. Tabares-Velasco, W. Bustamante, A critical review of heat and mass transfer in vegetative roof models used in building energy and urban environment simulation tools, Appl. Energy 232 (2018) 752–764.

B.Y. Schindler, L. Blank, S. Levy, G. Kadas, D. Pearlmutter, L. Blaustein, Integration of photovoltaic panels and green roofs: review and prediction of effects of electricity production and plant communities. J. Appl. Ecol. 52 (2015) 1074–1084.

Y. Li, R.W. Babcock, Green roofs against pollution and climate change. A review, Agron. Sustainability. Dev. 34 (2014) 695–705, https://doi.org/10.1007/s13593-014-0269-9.

S. Cascone, J. Cossa, A. Gaggiano, G. Pérez, The evapotranspiration process in green roofs: a review, Build. Environ. 147 (2019) 337–355, https://doi.org/10.1016/j.buildenv.2018.10.024.

S. Cascone, Green roof design: state of the art on technology and materials, Sustainability 11 (2019) 3020.

B. Dvorak, A. Volder, Green roof vegetation for North American ecotones: a literature review, Landsc. Urban Plann. 96 (2012) 197–213, https://doi.org/10.1016/j.landurbplan.2012.04.009.

S.C. Cook-Patton, T.L. Bauerle, Potential benefits of plant diversity on vegetated green roofs: a literature review, J. Environ. Manag. 106 (2012) 85–92, https://doi.org/10.1016/j.jenvman.2012.04.004.

N.A. Williams, J. Lundholm, J. Scott MacIvor, Do green roofs help urban ecosystems? J. Appl. Ecol. 51 (2014) 1643–1654.

J. Yang, Q. Yu, P. Gong, Quantifying air pollution removal by green roofs in Beijing, China, Environ. Pollut. 211 (2016) 78–84, https://doi.org/10.1016/j.envpol.2016.04.016.

S. Cascone, A. Gaggiano, G. Pérez, The evapotranspiration process in green roofs: a review, Build. Environ. 147 (2019) 337–355, https://doi.org/10.1016/j.buildenv.2018.10.024.

S. Cascone, J. Cossa, A. Gaggiano, G. Pérez, The evapotranspiration process in green roofs: a review, Build. Environ. 147 (2019) 337–355, https://doi.org/10.1016/j.buildenv.2018.10.024.
