Chapter 3
Climates and Microclimates: Challenges for Extensive Green Roof Design in Hot Climates

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Abstract Green roof systems have been developed and adopted in the temperate and cool-temperate climates of Europe and North America. Although these regions can get extreme weather, they generally do not experience climatic extremes of high temperatures, prolonged drought, and intense rainfall events of tropical and subtropical regions. This presents challenges for green roof design to not only provide adequate growing conditions for plants, but also to improve roof performance with respect to intrinsic (e.g. cooling building, extension of roof membrane lifetime) and extrinsic (e.g. flash flood mitigation, building cooling, reduction of heat island effect) benefits. Therefore, the components of conventional green roof including plant palette, growing media composition and the other synthetic layers need to be modified. The characteristics of green roof water retention, plant water availability, plant selection, and thermal properties are all critical factors which need to be adapted to help address the harsher environmental conditions and performance demands of hot climates. If these problems can be overcome, the combined environmental, ecological and sociological benefits suggest green roofs could be an imperative technology for towns and cities in tropical and subtropical regions of the world.

Keywords Green roof · Tropical and subtropical climates · Growing substrate · Plant selection · Stormwater

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3.1 Introduction

3.1.1 The Characteristics of Hot versus Temperate Climates

Green roofs represent a synthesized ecosystem subject to environmental extremes for plants. Extensive green roofs are described as having a thin (<20 cm; 7.8 in) layer of growing media, and depending on elevation, subject to the extremes of high wind, high thermal load, varying air humidity and often limited plant availability (Oberndorfer 2007). In effect, surface weather and ground conditions are oftentimes poor predictors of green roof microclimate where air and soil conditions are exacerbated to such an extent that from a plant perspective the growing conditions are significantly compromised. These extreme stresses can be significantly amplified in warmer climates.

Historically, green roof systems have been recorded in different regions across Europe and Asia (Snodgrass and Snodgrass 2006), but the contemporary extensive green roof (henceforth "green roof") has largely been developed in the temperate and cool-temperate climates of Europe and North America (Aber and Melillo 1982; Williams et al. 2010). Although periods of heat and drought can impact temperate regions, compared to tropical and subtropical zones, temperate climates can generally be described as experiencing moderate rainfall spread across portions or most of the year (sporadic drought notwithstanding), cool or cold winters mild to warm summers and moderate diurnal temperate variation (Peel et al. 2007). By contrast, warm tropical and subtropical climates (henceforth "hot climates") have cool to warm winters and warm to hot summers with rain events distributed either through the year (e.g. wet tropical) or seasonally (e.g. hot arid or Mediterranean) depending on geographic location. In hot climates the conditions of increased water (too much and too little) stress and high temperatures govern most of the challenges of green roof design. These differences can have a direct effect on the ecological function of the green roof—heat stress (both above and below ground), periodic saturation, and periodic drought all dictate the ecological response and hence design of green roofs in warmer climates. In terms of plant ecology and plant selection perhaps the greatest consequence of hot climate environment is a broader ecological niche—the sedum-dominated roofs in temperate systems are characterized by high water use efficient, succulent plants capable of withstanding cold winters and warm summers on a shallow-well drained medium. Conversely, in many hot climates plants must with stand high leaf and root temperatures, prolonged drought and occasional prolonged media saturation. To be able to tolerate heat, drought and prolonged saturation suggest plants with a different ecophysiological niche. From a plant-selection perspective this may be overcome by paying less attention to the conventional, green roof, temperate-climate plant palette and selecting from regional florae adapted to these more stressful conditions. However, the characteristics of the growing media to mitigate extreme hydrological and thermal conditions may require significant redesign.

3.1.2 Temperate Green Roof Design challenges

Green roof design has traditionally focused on growing media composition and structural design optimized in terms of minimal cost and weight (roof load bearing) to achieve desired performance goals and to ameliorate soil microclimate and water availability to accommodate appropriate plants. Temperate climate extensive green roof design has thus been optimized so much so the ecological niche for green roof plants is very narrow (Snodgrass and Snodgrass 2006). This suggests that in warmer, non-temperate systems with greater climatic extremes (e.g. high daytime and night time temperatures, frequent flash flood events), green roof design may require revision. All green roofs potentially offer significant intrinsic (e.g. cooling building, extension of roof membrane lifetime) and extrinsic (e.g. flash flood mitigation, reduction of heat island effect) benefits. But all aspects of conventional green roof design—plant palette, substrate composition and profile design—may likely need to be modified to accommodate these different environmental conditions and performance expectations.

Plant selection for green roofs in temperature regions has focused mainly on shallow rooted, succulent plants which exhibit Crassulacean Acid Metabolism (CAM) in the family Crassulaceae and less commonly on a selection of herbaceous grasses and forbs native to temperature regions (Snodgrass and Snodgrass 2006). In terms of stormwater, thermal mitigation and habitat characteristics temperate green roofs, designed correctly, can perform well. However, translating this technology to warmer regions presents a challenging suite of climatic problems including: flash flooding, prolonged drought, high day and night-time air and soil temperatures and limited available water supply. Ironically, the benefits of green roofs in these warmer environments might hypothetically be more justified than in temperate climates, by providing mitigation performance for the very characteristics that challenge their design and implementation (Kaufman et al. 2007; Alexandri and Jones 2008; Simmons 2008).

In this chapter I identify the short- and long-term challenges and benefits of micro and meso-climate that affect green roof design in hot climates and describe evidence and propose theories to overcome them.

3.2 The Benefits and Problems of Green Roofs in Hot Climates

3.2.1 Emergence of Research

Until recently, efforts to successfully implement extensive green roofs in hot climates have been comparatively few. Williams et al. (2010) suggest the major barriers have been unfamiliarity with green roof technology and inexperience of the emerging green roof industry, lack of regionally relevant research and inappropriate carry-over of the design (substrates and drainage layers) and biology (species), from temperate regions directly to hot climates. However, over the last decade green roof hot climate research has been initiated in a few locations around the world including: Australia (Williams et al. 2010), Southeast Asia (Tan and Sia 2005), Southern (Mediterranean) Europe (Fioretti et al. 2010), Central America (Müller Garcia 2005), and in USA: Texas (Simmons et al. 2008; Volder and Dvorak 2014), Florida (Sonne 2006a; Wanielista et al. 2008), Georgia (Carter and Rasmussen 2006) and Hawaii (Cabugos et al. 2007).

The specific problems around hot climate green roof success include low species/individual plant survival rates, due to drought (Farrell et al. 2012) for other reasons to be discussed below, poor stormwater performance under high rainfall intensity (Simmons et al. 2008) or prolonged wet events and weediness (Williams 2010). Additionally, from an implementation perspective, the limited expertise of green roof technology and knowledge of realistic performance and absolute function among architects and landscape architects has inhibited broad adoption in hot climates (Williams 2010).

In many respects green roofs represent a novel technology, more so outside of temperate regions, and the lack of knowledge, records of failure and inevitable low implementation rates has dramatically inhibited further development of this technology in hot climates.

3.2.2 Water Retention and Plant Water Availability

The ability for roofs to retain stormwater can vary a lot among green roof types with some having little or no retentive performance despite manufacturers claims (Simmons et al. 2008). Media composition and depth (Monterusso and Rowe 2005), drainage and retention layers (Simmons 2008) and the growth form and physiology of the plant suite (Dunnett and Kingsbury 2004; Schroll et al. 2011) all can have a direct effect on water retention performance (FLL 2008). Paradoxically, to some extent green roof design has been driven by the need for the conflicting goals of good stormwater retention and adequate drainage (both in the media and immediately above the roof membrane), while at the same time leaving sufficient available water in the growing media for plant uptake storm water retention (FLL 2008). This requires water to be held in different states and/or in different component of the green roof system with plant available water held at field capacity or below in the growing media and storm water retained in the media and in other retention structures as absorbent mats or combined drainage-retention layers below the growing media. European green roof standards have focused on the provision or assumption that either plant selection or frequency of rainfall events can meet plant growth requirements while still maintaining good water retention qualities (FLL 2008). But these guidelines may fall short of the provision of performance requirements for hotter and wetter climates. Despite the recommendations for drainage and retention of water green roofs in hot climates have sometimes failed to perform (Williams et al.

2010; MacIvor et al. 2011). This may be due to inappropriate combination of specifications of media, drainage, plant selection etc. and it is difficult to tell whether or not guidelines have been closely adhered to (Dvorak 2011). For example, FLL (2008) guidelines suggest that the growing media, should exhibit a broad range of particle sizes where the larger fraction represented by a porous, mineral-based material such as expanded shale, expanded clay, recycled brick, tile, scoria or pumice depending on local availability works well for a variety of temperate green roof assemblages (Molineux et al. 2009). But this may not be ideal for all plants types on green roofs in other regions. For example, research has generally been in support of increased organic matter (greater than FLL recommendations) to aid both plant establishment and especially to improve plant available water (Molineux et al. 2009). The problem with excessively increasing organic matter this is that under warm and wet conditions organic matter in the growing media may rapidly decompose under increased bacterial and fungal biological activity, dramatically reducing effective root volume. Even though some organic matter is continually added by vegetative components, high levels of organic matter are unlikely to be maintained. This suggests that other stable components meet the positive water retention (and other characteristics of organic matter) be substituted, for example hydrophilic gels, perlite and vermiculite which hold water, air and have high cation exchange capacity for plant nutrient supply (Getter and Rowe 2006; Sutton et al. 2012).

The ability for green roofs to be able to pump (evapotranspire) water out of the green roof while at the same time maintaining adequate plant water in the growing availability is a conundrum (Chap. 4). Keeping water loss to a minimum is related to plant transpiration, media evaporation and water-holding capacity within the media. Transpiration is minimized using plants with high water use efficiency, which is one attraction of succulent CAM plants, characterized by low stomatal conductance (Korner et al. 1979) and minimized night-time transpiration. However, removal of water from the substrate is desirable to optimize long-term storm water retention during wet seasons: in wet seasons with high frequency rain events the faster the green roofs can remove water from the roof system the better it can absorb the next event. Therefore plants that can switch between low transpiration in dry periods and high transpiration in rain events i.e. facultative CAM, or equally broad soil water niche plants such as some prairie grasses and forbs would be ideal (Wolf and Lundholm 2008; Sutton et al. 2012).

But even plants with high water use efficiency, the plant available water can decline quickly following precipitation/irrigation events especially in shallow media (Van Woert et al. 2005). This implies that where supplemental irrigation is unavailable the need to use plants with very high drought tolerance regardless of succulence and photosynthetic pathway is mandatory (Farrell et al. 2012). One alternative is to design a roof that simulates other hot climate landscapes with annual seeds, bulbs or other cryptophytes (plants which maintain living tissue below ground and seasonally invisible) only emerge under favorable conditions. Such a 'brown' roof may not be most desirable aesthetically or even general performance but certainly suggests that they are worth investigation.

Evaporation from the surface is dependent on both air and soil conditions. Therefore optimizing canopy cover to shade the soil surface needs to be balanced by transpirational characteristics of the plant. In cool climates the effect of shading may be less important than other microclimate effects such as precipitation and media moisture properties (Wolf and Lundholm 2008). Conversely, in hot climates with exceptionally high surface temperatures up to 90 °C (Williams et al. 2010), canopy shading, particularly in dry season may be important in influencing media water availability.

Many commercial green roof manufacturers utilize additional water retention layers (porous/capillary blankets or 'egg carton' bucket layers Fig. 3.1) to improve storm water retention performance of the roof and can be very effective (e.g. Miller and Narejo 2005; Berghage and Gu 2009). Ironically, some of these drainage/retention layers are usually topped with a root barrier—making retained water effectively inaccessible to plant roots. In climates where water availability is at a premium this is an exceptional inefficient use of resources. Destruction of four-year experiment green roofs in Texas however showed that aggressive roots followed moisture gradients and often compromised these root barriers (Fig. 3.1). An alternative to this is to use hydroponic foam in place of a standard retention layer (Fig. 3.2). This

Fig. 3.1 Four-year old roots on a destructed green roof passing through root barriers into drainage/retention layer. (*Mark Simmons*)

Fig. 3.2 Experimental hydroponic foam layer used beneath the growing media to accommodate both stormwater retention and providing plant available water Note the roots both above and penetrating through foam layers (*Mark Simmons*)

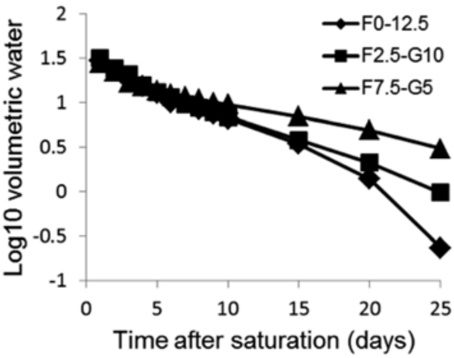

Fig. 3.3 Dry-down curves of vegetated trays containing different green roof growing media. (♦): No hydroponic foam layer, 12.5 cm growing media; (■): 2.5 cm hydroponic foam layer, 10 cm growing media; (▲): 7.5 cm hydroponic foam layer, 5 cm growing media (M.T. Simmons (2012) unpublished data)

provides for the retention of storm water retention while still simultaneously allowing accessibility to available water by roots. Trials in Texas indicate that hydroponic foam significantly prolongs the plant availability of water increases by reducing the rate of loss of total volumetric water content over time (Fig. 3.3). The wide range of commercial and potential products to aid water retention/availability is somewhat confusing and if performance is to be optimized then investigation and standardization (e.g. ASTM) is going to be essential to further green roof development in these harsher environments (Miller and Narejo 2005).

3.2.3 Root Temperature and Media Composition

Plant physiological processes are highly sensitive to temperature. Most vascular plant roots have a much narrower temperature envelope of performance compared to the aboveground stems and leaves. Although species specific, generally the operational temperature range of root physiological processes are from 4 °C to 30 °C. Above that upper temperature, respiration and other root processes decline rapidly and certain processes, particularly the synthesis of secondary materials slow down until above 48 °C where they stop and root mortality results (Xu and Huang 2000; Urban 2008; Sutton et al. 2012). Even in arid CAM plants these upper limits to root function still apply (Drennan and Nobel 1998).

Roof surface (waterproof membrane) temperatures in summer can easily exceed these critical temperatures. In Texas, roof temperatures have been recorded at 56 °C in early (spring) growing season (Simmons et al. 2008) and can exceed 70 °C in summer (Simmons et al. 2008), mid 50 s°C in Florida (Sonne 2006b) and up to 90 °C recorded in Australia (Williams et al. 2010). Simmons et al. (2008) recorded temperatures in weekly irrigated growing media (5 cm (2 in) below surface) ranging between 25 °C to 40 °C, similar to values recorded on green roofs in Singapore (Tan and Sia 2005) and Florida (Sonne 2006b) suggesting that there is sufficient heat flux through conduction, radiation and convection to limit root growth in at least the top layers of the media.

Excavated plants from extensive roofs exhibited low root density in the top 5 cm of the growing media suggesting that in some growing media the top layer may be redundant either due to temperature, high porosity or more water availability in these upper layers (Fig. 3.4). Collectively this evidence indicate that modification

Fig. 3.4 Four-year-old grass (Bouteloua dactyloides) grown on experimental green roof exhibiting low root density in upper layers of the growing media (10 cm total media depth) (Mark Simmons)

of media composition, specifically to alter the thermal conductivity (λ) and heat capacity, may help to improve the green roof environment in extreme climates. Media composition may also be critical to plant establishment. Any component that increases water retention will likely improve plant survival. MacIvor et al. (2011) examining a range of succulents, grasses and forbs on green roof modules in Toronto, Canada, concluded that plant cover and biomass declined on a media based on the FLL specifications of low organic matter. The coarse component of many commercial growing media can be naturally occurring (scoria, lava rock pumice), recycled (brick, tile) or processed (expanded shale or clay). These components often makes up the bulk of volume and are included to provide ballast, root anchor, and a site for plant available water and nutrients. However these materials can present a problem in hot climates as they may exhibit high thermal conductivity, transmitting heat through conduction (convection and radiation have a relatively small role in growing media thermal flux) down into the sensitive root-growth zone. One way to mitigate this to protect roots from high temperatures is to increase thermal insulation characteristics of the media by addition of organic or other non-coarse, lightweight materials like vermiculite that are known to have low thermal conductivity. Laboratory trials (Simmons, unpublished data) demonstrated that lightweight, porous organic and inorganic material added to media (50 % by volume) not only improved volumetric water content ($\theta = 0.248$ $m^3.m^{-3}$; brick plus porous matter $\theta = 0.465$ $m^3.m^{-3}$) but also reduced thermal conductivity across a range of soil water potential (ψ) (Fig. 3.5a). The trade-off of high organic volume is that, with a few exceptions, most commercially-available organic amendments used in green roof media break down over time—and with warmer climates this process is accelerated, reducing valuable root volume and causing plant decline or death. Additionally, these same laboratory trials revealed that one commercially available expanded clay-based material also demonstrated

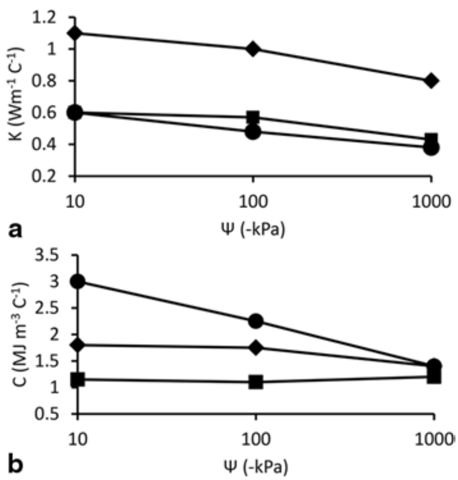

Fig. 3.5 A the relationship of thermal conductivity (κ) and B heat capacity (C) to growing-media water potential (Ψ) of three substrates: crushed brick (♦); crushed brick and porous organic/inorganic matter (■, 50:50 by volume) and a commercially available substrate (● expanded clay and organic/in-organic matter 50:50 by volume) (M. T. Simmons, T. Caldwell and M. R. Bright unpublished data)

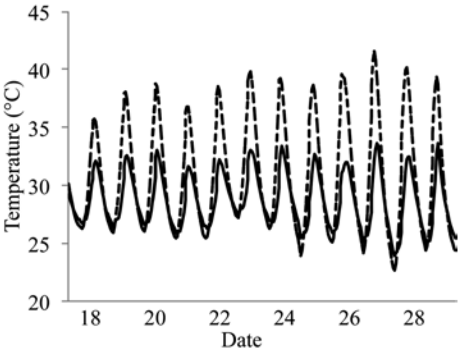

Fig. 3.6 Diurnal temperature flux of 10 cm deep growing media (2 types) on green roofs over 10 days (average high temperature 33 °C) in August in Texas. Solid line = media comprised of decomposed granite, perlite and organic matter; Dashed line = media comprised of expanded clay, expanded shale, sand and organic matter (M.T. Simmons unpublished data)

unusually high heat capacity (Fig. 3.5b). This could present a significant problem in hot climates where the cumulative effect of slow overnight cooling during warm months could lead to the build-up of excessively high temperatures in the media over time. Comparison of substrate temperature over an 10 day period in summer 2007 of test plots showed that a commercially available expanded clay/shale-based media did slowly reach higher maximums (consistently exceeding the critical 30 °C temperature where root function becomes impaired) compared to media containing decomposed granite and perlite (Fig. 3.6). While, without further investigation, it is not possible to determine the mechanism that drives this response, it does highlight the need for further investigation and specification of thermal properties of growing media for green roofs in hot climates.

3.2.4 Thermal Benefits in a Hot Climate

One key attribute of green roofs is their thermal benefits both to the building and immediate environment (Chap. 9). These characteristics of green roofs are no more important than in hot climates where daily maximum air temperature are higher, last longer through the day and persist over much or all of the year. Roof surface temperatures have been shown to be dramatically decreased in the presence of green roofs with deltas of 20 °C in Florida (Sonne 2006b), 38 °C in Texas (Simmons et al. 2008) and up to 60 °C in Japan (Wong 2003). This has mainly been attributed to the combination of shading (Wong 2003), solar reflectivity (Castleton et al. 2010), insulation (Barrio 1998), and evaporative cooling (Onmura et al. 2001) of all or some of the green roof components. This has several direct benefits. Firstly a damping of the diurnal temperature variations at the roof membrane combined with protection from ultra-violet radiation can extend the membrane integrity (Liu and Baskaran 2003). Secondly, it can reduce the energy budget of the building. The reduction of thermal flux through the building below the green roof can translate to savings in the build of up to 4 °C in temperate systems, to up to 15 °C in subtropical (Simmons et al. 2008). In a green roof test in Athens, Greece demonstrated that a building with a regular roof experienced internal air temperatures over 30 °C for 68 % of total time during a three-day test period in summer. Conversely, the green roofed building exceeded 30 °C only 15 % of the time. Whatever the mechanism this mitigation of thermal flux can amount to significant cost savings. Dunnett and Kingsbury (2004) suggest that there is an 8 % reduction in electricity use for air conditioning for every 0.5 °C decrease in internal temperature and if this model can be extrapolated to other regions, would represent a significant saving in hotter climates. In Florida, Sonne (2006b) estimated an energy reduction (cooling) of around 50 % for a two-story building with a 150 m^2 green roof. It has been argued however that green roofs for their thermal mitigation properties alone may not justify the resources as standard insulation is relatively inexpensive. According to one model on well- insulated buildings energy savings drop from 48 % for non-insulated to 2 % for well-insulated buildings.

Similarly, green roofs have been shown to cool ambient air temperatures that can translate to the larger scale especially in hot climates (Alexandri and Jones 2008). Microclimate modification by green roofs can affect both immediate local conditions by directly cooling air (Wong 2003), increasing reflectivity and by reducing long-wave radiation through the diurnal temperature cycle all of which can modify the urban heat-island effect (Getter and Rowe 2006; Oberndorfer et al. 2007, Santamouris In press). Even in the continental temperature climate of Toronto, Canada a study concluded that with only 6 % of total roof space dedicated to green roofs would result in a reduction of 1–2 °C in summer (Bass et al. 2003).

3.2.5 Plant Selection

Clearly, tolerance to drought, high temperatures (air and soil) and ability to tolerate media saturation for periods of time are desirable features. This suggests that plant selection for hot climates should examine those species with broader ecological niche and habitat generalists not specialists. A mix of growth forms for hot climate green roofs, may be the solution to optimize performance across all climate conditions through the year (MacIvor 2011; Wolf and Lundhom 2008). Succulence or CAM, although beneficial is not the only method of drought survival. Ability to reduce biomass through drought deciduousness, (Farrell et al. 2012) or avoidance as a seed (therophyte) or high water use efficiencies can all be successful drought survival strategies. Sedums of temperate climate origin although widely used for green roofs in Europe and North America, with a few exceptions, may not be suitable in hot climates as the exhibit relatively weak ability to fix CO_2 above 20 °C (Williams 2010; Livingston 2004). At night in hot climates, when gas exchange takes place stomata open in CAM plants, temperatures can easily exceed this through much of the growing season, and at high vapor pressure gradients and night time temperatures (> 30 °C) CAM plants have been shown to exhibit significant decreases in net CO_2 gain (Herppich 1997; Livingston et al. 2004). While all the mechanisms that inhibit the use of the temperate-climate Sedums on green roofs in hot climates remain unidentified, evidence from these and other studies suggest that high day and/or night-time temperatures may be responsible. Some Sedums including non-European Sedums however have been shown to perform with some success in green roofs in Texas (Volder and Dvorak 2014) and under greenhouse conditions in the warm/temperate climate of Melbourne, Australia.

Farrell et al. (2012) had good drought survivorship of two Mexican and one Caucasian Sedum species that performed better than two succulent natives. In a Texas study survivorship on 18 extensive green roof units (Simmons et al. 2008) over 5-year period demonstrated that plant physiognomy or guild was not necessarily a prediction of plant survival (Fig. 3.7). Woody and non-woody forbs generally did less well than most graminoids and succulents. Some grasses did moderately well especially warm season bunch grasses, while a cool season grass, and more hydrologically-mesic graminoids did not. The three CAM species were better performers with up to 100 % survivorship (Fig. 3.7). With more supplemental irrigation

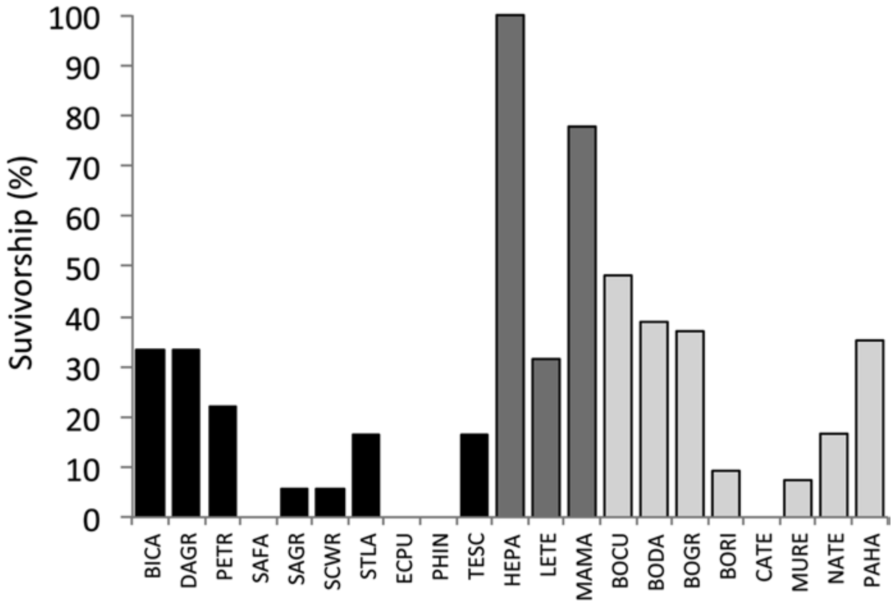

Fig. 3.7 The mean 5-year survivorship of 21 regionally native species on 18 green roof units in Austin Texas. Guilds: Black bar = forb; Dark grey bar = succulent/CAM; Light grey bar = graminoid. Species: BICA = Bignonia capreolata; DAGR = Dalea greggii; PETR = Penstemon triflorus; SAFA = Salvia farinacea; SAGR = Salvia greggii; SCWR = Scutellaria wrightii; STLA = Stemodia lanata; ECPU = Echinacea purpurea; PHIN = Phyla incisa; TESC = Tetraneuris scaposa; HEPA = Hesperaloe parviflora; LETE = Lenophyllum texanum; MAMA = Manfreda maculosa; BOCU = Bouteloua curtipendula; BODA = Bouteloua dactyloides; BOGR = Bouteloua gracilus; BORI = Bouteloua rigidiseta; CATE = Carex texensis; MURE = Muhlenbergia reverchonii; NATE = Nassella tenuissima; PAHA = Panicum hallii. Media depth = 100 mm. Irrigation regimen: minimum of 50 mm per month either by rainfall, irrigation or both (M T Simmons, unpublished data)

and improved media characteristics overall survivorship would likely increase. In another Texas study of fifteen different species of different geographic origins and different growth forms Dvorak and Volder (2012) found that only four of the fifteen species faired consistently well, demonstrating 100 % survival over three years and all were succulents.

Plant architecture may also have an influence on survivorship. Liu et al. (2012) examined the physiology and survival of thirty-one plants on green roofs in the humid subtropical climate of central Taiwan. The most successful species were those that exhibited succulent foliage, leaf hairs/spines, CAM and elevated plant height (up to 35 cm tall). Such physiological strategies to deal with drought stress are also common in grassland ecoregions and consequently lend themselves to green roof environments. Wolf and Lundholm (2008) in a study in cool temperate location (Nova Scotia, Canada) suggested that beyond the genus Sedum, some grasses were able to respond to water stress and lived longer-lived than succulents and woody plants and should be considered as further candidates for the green roof plant palette. Similarly, Sutton et al. (2012) reviewed grasses and forbs from North American prairie that had been used on green roofs under different irrigation regimens and

Fig. 3.8 Green roof on a residential building in Texas (Green Roof: Ecosystem Design Group, Lady Bird Johnson Wildflower Center, University of Texas at Austin Architects: Bercy Chen Studio LP)

Fig. 3.9 Green roof on a residential building in Texas (Green Roof: Ecosystem Design Group, Lady Bird Johnson Wildflower Center, University of Texas at Austin Architects: Bercy Chen Studio LP)

geographic locations and concluded that these could provide alternatives to Sedum species but stressed that more detailed studies are needed (e.g. Figures 3.8 & 3.9). One trait that may enhance the suitability of prairie grasses is that many grasses (and indeed many other species) are facultative mycorrhizal. This may help to improve performance by increasing effective root volume through the production of mycorrhizae, reducing water stress and nutrient uptake in a limited media depth of the green roof environment (Sutton et al. 2012).

Plant selection for some green roofs has mainly relied on tried successes of green roofs in temperate systems but more recently has examples from warmer climates (Dvorak and Volder 2013; Liu et al. 2012). This has led to some roof failure in hot climate and the basis for plant selection is undergoing an overhaul (e.g. Simmons et al. 2008; Liu et al. 2012; Sutton et al. 2012). While the issues of simple survival are obviously important, species selection would benefit from a fresh approach focusing on overall desired roof (e.g. storm water, thermal, and aesthetic characteristics), performance and letting that drive roof design and plant selection. That would mean selecting the most desired benefit(s), for example, drought tolerance, slow growth rate, then finding plant species or assemblages that meet these criteria. Finally, the extremes of conditions on hot climate green roofs suggest that plant selection screening should focus on species with a broader ecological niche selection - i.e. generalists (e.g. plants that can tolerate drought, yet endure occasional saturation) and not specialists (e.g. a species constantly requiring well-drained conditions). This is especially important with respect to tolerance range of the plant species to both soil water and soil temperature.

3.3 Conclusions

3.3.1 Imperative of Green Roofs in Hot Climates

Large proportion of global population lives in cities in subtropical and tropical regions around the world. In cities with high densities and high proportion of impervious surface and limited green infrastructure (Shanghai—Tokyo, New Delhi, Mumbai, Hong Kong, Sydney) green roofs may be the only green strategy to improve essential ecosystem services. However, for green roofs to be successful, a more holistic approach and understanding of all performance benefits have to be understood and quantified. It is not enough for justification of green roof technology to focus on one performance feature, say water retention, as cheaper methods to achieve the same goal (e.g. retention pond at grade), or thermal benefits (e.g. reflective white roof) may be available. In other words, taken individually, green roof performance attributes may exhibit incremental benefits at unjustifiably high costs. However, the environmental, ecological and sociological benefits taken together make a sound case for green roofs and even an imperative technology for the future of our cities. As described above green roofs vary regarding plant and media traits due to the local climate and microclimate (Table 3.1)

Table 3.1 The differences in in roof characteristics and plant and media traits for green roofs in temperate, hot-arid and hot-wet climates

		Temperate Climate	Hot Arid Climate	Hot Wet Climate
Roof conditions	Max leaf/root temperature	Moderate	High	High
	Min leaf/root temperature	Low	Moderate-Low	Moderate
	Sustained period of high temperatures	Infrequent	Frequent	Frequent
	Sustained period of low temperatures	Frequent	Infrequent	Never
	Sustained period of saturation	Frequent	Occasional	Frequent
	Sustained period of drought	Infrequent	Frequent	Infrequent
Desirable plant traits	Cool climate succulent	✓		
	Warm climate succulent		✓	✓
	Cool season herbaceous	✓		
	Warm season herbaceous		✓	✓
Desirable media traits	Drainage	Well-poor	Well-moderate	Well
	Retention	Low-moderate	High	Moderate-high
	Thermal conductivity	Moderate	Low	Low

3.3.2 Research Questions for the Future

Media composition affects abiotic and plan roof performance. The seemingly infinite potential compositions need continued systematic examination to meet the challenges of specific environments. Water retention and drainage, and thermal characteristics deserve particular attention.

Plant selection for hot climate green roofs needs a shift of focus away from plant survival only and more to ward desired roof performance. Once this is established—storm water, building cooling etc. - then the roof can be designed and appropriate species selected accordingly.

Although the climate conditions will somewhat drive plant selection where climates are more seasonal (wet-dry; cool warm) and as climate change theory predicts more climatic stochasticity, the selection procedure should examine species with broad ecological niches with respect to soil water and soil and air temperature conditions.

Justification for green roofs will rely on the quantification all the potential environmental (e.g. storm water retention, thermal moderation), ecological (e.g. habitat) and sociological (e.g. access to green space) benefits collectively (Chap. 9) especially as many are not mutually independent.

The FLL standards have been useful metrics around which green roofs can be designed, built and experimented with, and have been successful in a range of climates (Philippi 2005; Dvorak 2011). However, these standards should not limit the development of green roof growing media specifications for hot climates where innovative ways to improve thermal and hydrologic characteristics are needed. The investigation and current development of standards (e.g. FLL ASTM) of all green roof components will be essential for the adoption of green roofs as a major contributor to green infrastructure.

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