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Research Paper

Assessing climate-adaptation effect of extensive tropical green roofs in cities

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HIGHLIGHTS

- Urban greenspaces can bring multiple benefits and climate adaptation to cities.
- Green roofs offer plausible solution to greenspace-deficient compact cities.
- Detailed field experiment allows in-depth assessment of greenroof thermal performance.
- Sedum roof stores some heat to warm near-ground air and indoor space to intensify UHI.
- Peanut roof cools near-ground air but creates heat-sink to induce indoor cooling load.

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ABSTRACT

Many cities have inadequate green infrastructures and cannot benefit from ecosystem services brought by greenspaces. Global warming and urban heat island (UHI) effect impose a dual warming impact on cities, especially compact ones. Green roofs offer a plausible solution for climate adaptation. In compact humid-tropical Hong Kong, two green-roof and a control bare-roof plots were installed on a high-rise building. Precision sensors were installed along a holistic vertical temperature profile extending from outdoor air to roof surface, green-roof material layers, and indoor ceiling and air. Three apartments under the plots were kept vacant to monitor air-conditioning energy consumption. The comprehensive-systematic data allowed in-depth analysis of thermal performance of vegetation (Sedum and Perennial Peanut) and weather (sunny, cloudy and rainy) in summer. Intense solar radiation at Control plot triggered significant material heating, which in turn warmed near-ground air to intensify UHI effect and indoor space to lift energy consumption. Sedum plot with incomplete plant cover, sluggish transpiration and limited substrate moisture storage had feeble evapotranspiration cooling. The warmed roof passed heat to near-ground air and subsurface layers to impose a small indoor cooling load. Peanut plot with high transpiration rate can significantly cool foliage surface and near-ground air to ameliorate UHI. Its high moisture-holding capacity, however, can generate an appreciable heat-sink to push heat downwards and increase indoor cooling load. Practical hints on green roof design and management were distilled from the findings for application in Hong Kong and beyond and to contribute to climate-resilient cities.

1. Introduction

Many cities in developed and especially developing countries have inadequate urban green infrastructure (UGI) to ameliorate the harsh impacts imposed by excessive gray infrastructure (Svendsen, Northridge, & Metcalf, 2012). With intensification of global warming superimposed on urban heat island (UHI) effect, cities are literally heating up, pleading for sustainable and cost-effective climate-adaptation solutions. Urban green spaces (UGS) with vegetation and unsealed soil can offer cool island effect to alleviate the UHI effect and reduce energy consumption (Akbari & Konopaci, 2005; Castleton, Stovin, Beck, & Davison, 2010). At the street level, roadside trees can provide a thermally comfortable environment to pedestrians in the real and perceived senses (Klemm, Heusinkveld, Lenzholzer, & Van Hove, 2015). To a certain extent, green cities with generous provision of UGS are pre-adapted to be climate-resilient (Getter & Rowe, 2006; Jones, Hole, & Zavaleta, 2012; Mathey, Rößler, Lehmann, & Bräuer, 2010). Municipal governments can probe and muster community support to enhance UGI to prepare cities for climate adaptation (Byrne, Lo, & Yang, 2015).

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Compact cities with few interstitial green covers, however, cannot benefit liberally from their natural ecosystem services of cooling, cleaning and ventilation. The prevalence of hard covers vis-à-vis green and blue surfaces can contribute notably to human discomfort with implications on human health especially in hot and dry cities (Mazhar, Brown, Kenny, & Lenzholzer, 2015). A common societal response to rising temperature is to increase the use of air-conditioning in an attempt to maintain the accustomed level of human comfort (Parsons, 2003). The consequential upstream-cum-downstream generation of sensible heat, greenhouse gas and air pollutants, creates a positive-feedback vicious circle. To be freed from the bondage and to contain the sprawling ecological footprint of cities, innovative approaches are called for.

The opportunities to increase UGS in new towns or new or renewal development of existing cities through spatial and climate-responsive planning should not be squandered (Brown, Vanos, Kenny, & Lenzholzer, 2015; Matthews, 2015). Nevertheless, the scope for UGS expansion is limited in established compact cities. Greenspace provision, however, does not need to be confined to the ground level. Numerous building rooftops, which tend to be left bare, offer potential sites for green roofs (Milburn, Fernández-González, Jones, Solano, & Martínez-Wong, 2013). The external vertical surfaces of building envelopes provide chances for green walls. Such elevated UGS can supplement the existing stock to reinforce provision of ecosystem services in built-up areas. Collectively, they constitute a valuable and substantial yet largely neglected if not wasted resource. They can help to ameliorate the local urban heat islands that suffer from overheating problems (Emmanuel, 2015). Their potential contribution to climate-proofing cities (Hall, Handley, & Ennos, 2012; Tzoulas et al., 2007) could be mobilized by a proactive greenery infilling policy above the ground level.

Green roofs can usher nature's clean and free evapotranspiration passive cooling (Jim & Tsang, 2011a; Tan, Wong, Chen, Ong, & Sia, 2003; Voyde, Fassman, Simcock, & Wells, 2010), driven by solar radiation, into the heart of the city and proximal to people (Jim, 2012; Köhler, 2004; Theodosiou, Aravantinos, & Tsikaloudaki, 2013). The cooling effect extends upwards to the ambience and downwards to the building fabric and indoor space (Del Barrio, 1998; Givoni, 2011; Teemusk & Mander, 2009; Wong, Tan, & Chen, 2007). Green roofs bring collateral benefits of accessible and safe amenity spaces, clean air, noise abatement, and associated contributions to physical and mental health. At the city scale, the UHI effect and smog formation which is catalyzed by high temperature can be alleviated (Bass, Krayenhoff, Martilli, Stull, & Auld, 2003; EPA, 2009; Susca, Gaffin, & Dell'Osso, 2011). They can reduce the quantity and improve the quality of urban stormwater discharge, with implications on flood prevention, quality improvement in receiving water bodies, and reduced capital and maintenance costs of stormwater drainage systems (Berghage et al., 2009; Carter & Jackson, 2007). Their benefits can be shared with wildlife which can use green roofs and walls as refuges or habitat islands for roosting and feeding, and as stepping stones to penetrate the city to enhance urban biodiversity (Brenneisen, 2006; English Nature, 2003).

Solar energy reception at the roof affects temperature in the air above the green roof, on the roof or vegetation surface, and in the green-roof material layers. In turn, the heat retained by the green roof system can transmit downwards to underlying indoor space. The heat that fluxes downwards from the roof could increase energy consumption by air-conditioners especially during summer. Understanding this relationship could throw light on environmental benefits of green roofs in compact urban milieu. The results could provide practical hints on the choice of plant species and green-roof design for cost-effective application of the innovative technology.

A control experiment was designed to evaluate the effect of two extensive green roofs with different vegetation and associated substrate design on air-conditioning electricity consumption in the underlying apartments. The study develops a new dimension to reinforce existing findings on the effect of green roofs on outdoor–indoor temperature and building energy performance especially in the warm season under different climates (e.g., Blanusa et al., 2012; Castleton et al., 2010; Getter, Rowe, Andresen, & Wichman, 2011; Jim, 2014; Niachou, Papakonstantinou, Santamouris, Tsangrassoulis, & Mihalakakou, 2001). The living quarters provide a real-world setting to assess the relationship between green-roof effect and energy use. Instead of employing assumptions to compute estimated energy use in previous studies, this research directly acquired electricity consumption data with precision energy loggers. As the literature lacks experimental data on actual electricity consumption for space air-conditioning in relation to green roofs, this study could fill the knowledge gap.

Using Hong Kong as a good compact-city example, this study assessed the key climate-adaptation functions of green roofs in the tropical weather zone. With the help of controlled field experiments, it aimed at three objectives: (1) evaluating the temperature moderation function of two types of green roofs in a holistic vertical profile extending from the outdoor ambience to roof surface and material layers, and to indoor ceiling and air; (2) assessing the air-conditioning energy consumption patterns and saving in relation to the green roofs; (3) distilling from the findings practical recommendations on design and management of green roof for buildings in tropical cities. The study focuses on three weather scenarios of the summer season to highlight thermal-energy performance under hot conditions.

2. Study area and methods

2.1. Study area

Hong Kong is situated at the northern edge of the tropical zone, close to the Tropic of Cancer at 22° N latitude and 114° E longitude, at the south coast of China, and on the east side of the Pearl River Estuary. The humid-subtropical climate is notably influenced by the region-wide Asian monsoon system. Summer is hot-humid with frequent showers, thunderstorms and occasional typhoons. The warm months, running from May to September with the hottest days exceeding 33 °C, coincide with the rainy season with annual precipitation of over 2300 mm. The rather short and mild winter has average temperature above 10 °C. With a long, hot and humid period, air-conditioning is used in most commercial, residential and institutional buildings.

Experimental green roof plots were established on the top of a high-rise residential block in Shin Ming Estate in Tseung Kwan O New Town in Hong Kong (Figs. 1 and 2). It is a public housing estate built by the government and occupied in 2011, catering to the low-income group. The rooftop of the 33-storey building was reserved for the experimental study. Below the three experimental plots, three domestic apartments were kept unoccupied in the study period for indoor monitoring.

2.2. Experimental plots and design

The subject roof was equipped with the full range of five material strata resting on the concrete roof slab, from the bottom upwards: 25 mm screed, 1 mm waterproof membrane, 40 mm polystyrene foam, 25 mm cement-sand bedding, and 35 mm precast concrete tile. Such construction details are commonly adopted in Hong Kong. The finished roof surface has a 2% gradient to shed water to drainage channels and drain pipes.

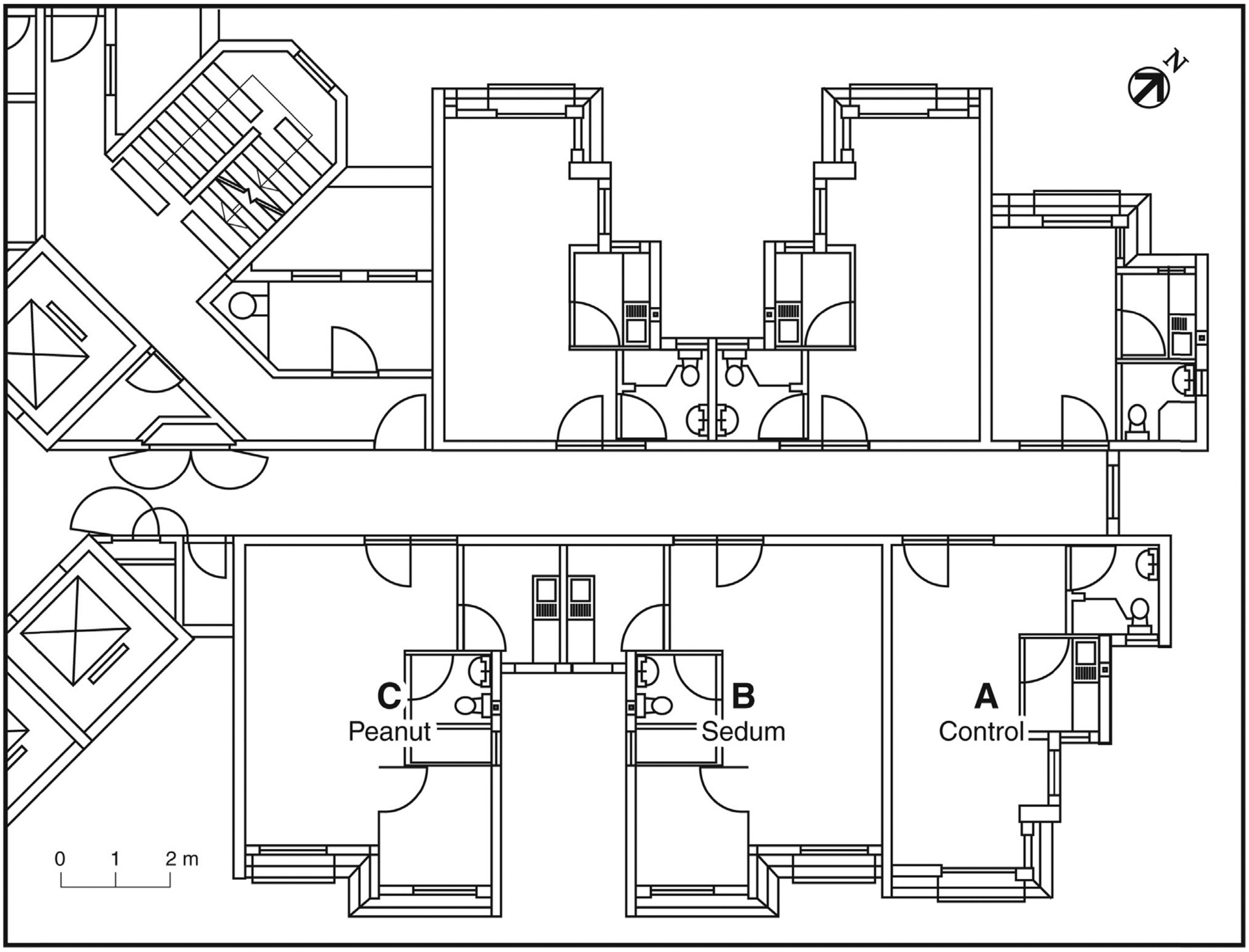

Fig. 1. The three experimental plots on the rooftop of the high-rise building which matches the three domestic flats situated below them.

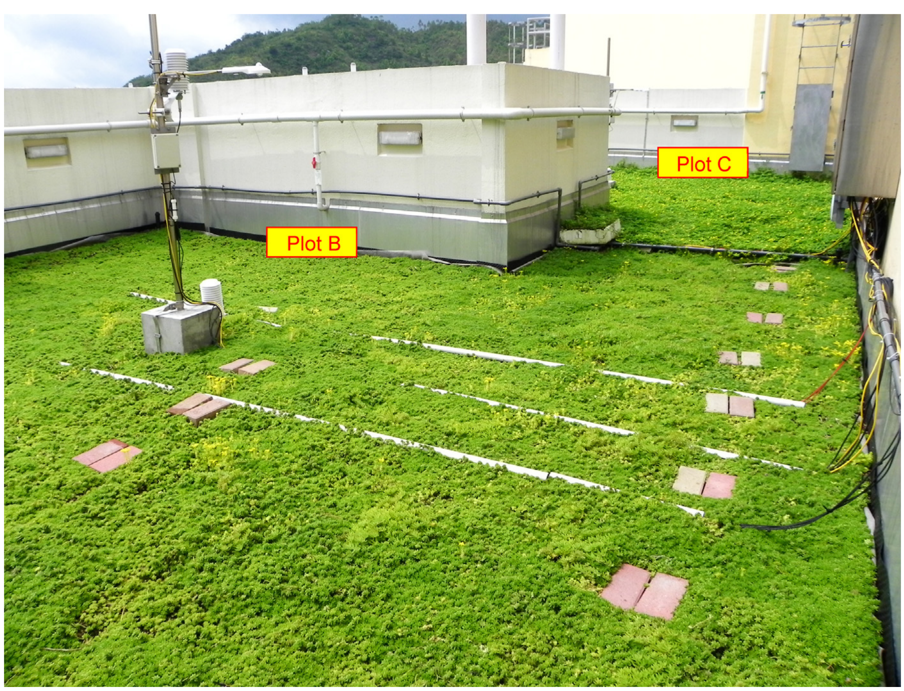

Fig. 2. The two extensive green-roof experimental plots established on the rooftop of the study site. Plot B (Sedum) is in the foreground, and Plot C (Perennial Peanut) in the background. Note the instrument stands which are placed near the center of each plot.

Table 1
Key parameters of the three experimental plots.

Plot	Treatment	Species	Growing medium
A	Control	n.a.	(Bare concrete tile)
B	Sedum	*Sedum mexicanum*	Calcined clay pellets with compost (50 mm)
C	Perennial Peanut[a]	*Arachis pintoi*	Completely decomposed granite with compost (50 mm) Rockwool (50 mm)

[a] Abbreviated as "Peanut" plot in the text.

The rooftop of about 200 m^2 was divided into three plots of approximately equal size, which aligned with the three apartments below them (Figs. 1 and 2). Plot A ('Control plot') was left bare as the control. Plots B and C were devoted to two groundcover plant species with divergent growth form and physiology (Table 1). The three apartments have main windows and external walls facing the same southeast direction (Fig. 1). Windows and external walls in other directions are situated in the indented parts of the building and well shielded from direct sunshine. The only exception is the northeast-facing external walls and windows of flat A which is situated at the end of the building wing. The possible input of solar energy on this side has been mitigated by installing two layers of thermal-insulation gypsum boards with mineral-wool center from floor to ceiling. The experiment assessed the thermal-energy effect of two green roof plots vis-à-vis the upwards (outdoor), internal (green-roof layers) and downwards (indoor) temperatures.

Plot B ('Sedum plot') was planted with Mexican Sedum (*Sedum mexicanum* Britton, Crassulaceae), a drought-tolerant perennial native to Central America. The succulent plant has xerophytic features such as needle-like foliage, thick cuticles and limited surface area to reduce transpiration and conserve moisture (Voyde et al., 2010). It represents the few Sedum species adapted to tropical climate (Snodgrass & Snodgrass, 2006; Stephenson, 1994). In the moisture-deficit state, Sedums may switch to special Crassulacean acid metabolism (CAM) photosynthesis, with closure of stomata and reduction of transpiration especially in daytime. Carbon, stored in its leaf tissues at nighttime, is released for photosynthetic use during stomatal closure in daytime. From cuttings, a full cover was achieved after one growing season.

Plot C ('Peanut plot') was planted with Perennial Peanut (*Arachis pintoi* Krapov. & W.C. Greg., Fabaceae), a perennial groundcover herb native to tropical South America. It adopts the common C3 photosynthesis pathway of broadleaved plants. The nitrogen-fixing legume tolerates high temperature and resists pests and diseases (Australian Centre for International Agricultural Research, 2013; College of Tropical Agriculture and Human Resources, 2013). It has been found to perform well on tropical roofs (Tan & Sia, 2008). From stem cuttings, the vigorous herb achieved in one growing season a dense mat of stolons and foliage.

2.3. Green roof design and installation

The modern green roof system (Nophadrain, Kirkrade, The Netherlands) was constituted by multiple layers of synthetic and natural materials, which are certified by the rigorous German green roof standard (FLL, 2008). Laid in sequence on the concrete tiles, they included from bottom upwards (Fig. 3): 0.5 mm low-density polyethylene root barrier sheet, 25 mm high-impact polystyrene drainage layer, 1.0 mm non-woven polypropylene geotextile filter, 50 mm hydrophilic rockwool (silica mineral fiber board) water retention layer, and 50 mm substrate layer. The field capacity values of mineral substrate and rockwool are estimated to be, respectively, 28% and 26% by volume proportion (Jim & Peng, 2012).

To meet the differential substrate and moisture needs of two plant species, the two green roof plots had different designs. For Plot C, the substrate was a mineral soil mixed with 20% (v/v) mature compost. The mineral fraction is locally available completely decomposed (weathered) granite with sandy-loam texture and free drainage (Jim, 1996). For Plot B, the substrate is horticultural calcined or heat-treated clay pellets which are pottery-like (Handreck & Black, 2002). It meets the requirements of Sedum which cannot tolerate too much soil moisture. The pellets have plenty of large pores to facilitate drainage and aeration, limited water-holding capacity, and some cation exchange capacity. The field capacity, contributed mainly by the compost held in the interstices of the large pellets, is estimated to be 10%.

The rockwool layer furnishes a porous and yet extremely lightweight mineral wool (silica) medium for plant growth. The dry weight is merely 6 kg/m^2, and saturated weight 46 kg/m^2, reflecting exceptionally high porosity to achieve 80% (v/v) water-holding capacity. Roots can grow readily into the highly porous material. By partly replacing the heavy soil layer and maintaining water supply, green roofs can be installed on buildings with a low load-bearing capacity. The rockwool layer is deleted in Plot B.

An automatic sprinkler irrigation system (Rain Bird, Tucson, AZ, USA) provided supplementary water supply. Its electronic controller was programmed to feed water in early morning at 5 L/m^2/day. Upon reaching an accumulated antecedent rainfall of 10 mm, the build-in rainfall sensor can switch off the pump to save water during the summer rainy season.

2.4. Environmental monitoring

The installation positions of environmental sensors are shown in Fig. 3. Temperature sensors were installed along a holistic vertical profile extending from outdoor air to roof surface and internal layers, and to ceiling and indoor air:

(a) Outdoor air: at 15 and 150 cm.
(b) Outdoor roof surface: exposed concrete tile surface at Plot A; green roof vegetation surface at Plots B and C.
(c) Green roof material layers: middle of substrate, rockwool, and drainage layers, and tile (green roof bottom below root barrier and resting on covered concrete tile).
(d) Indoor: ceiling surface, and air at 150 cm from floor.

The following environmental sensors were deployed at the experimental site:

(a) Outdoor air and green-roof material layers (substrate, rockwool, drainage, and tile) temperature: Platinum PT100 (8160.TFF for air, and 8160.TF for material layers, Lufft, Fellbach, Germany).
(b) Indoor air temperature: thermister (U14-001, Hobo, Bourne, MA, USA).
(c) Surface temperature at outdoor (vegetation and bare concrete tile) and indoor (ceiling): non-contact infrared radiometer (SI-111, Apogee, Logan, UT, USA).

A weather station was placed on the Control plot to record solar radiation (net radiometer, Kipp & Zonen, Delft, the Netherlands),

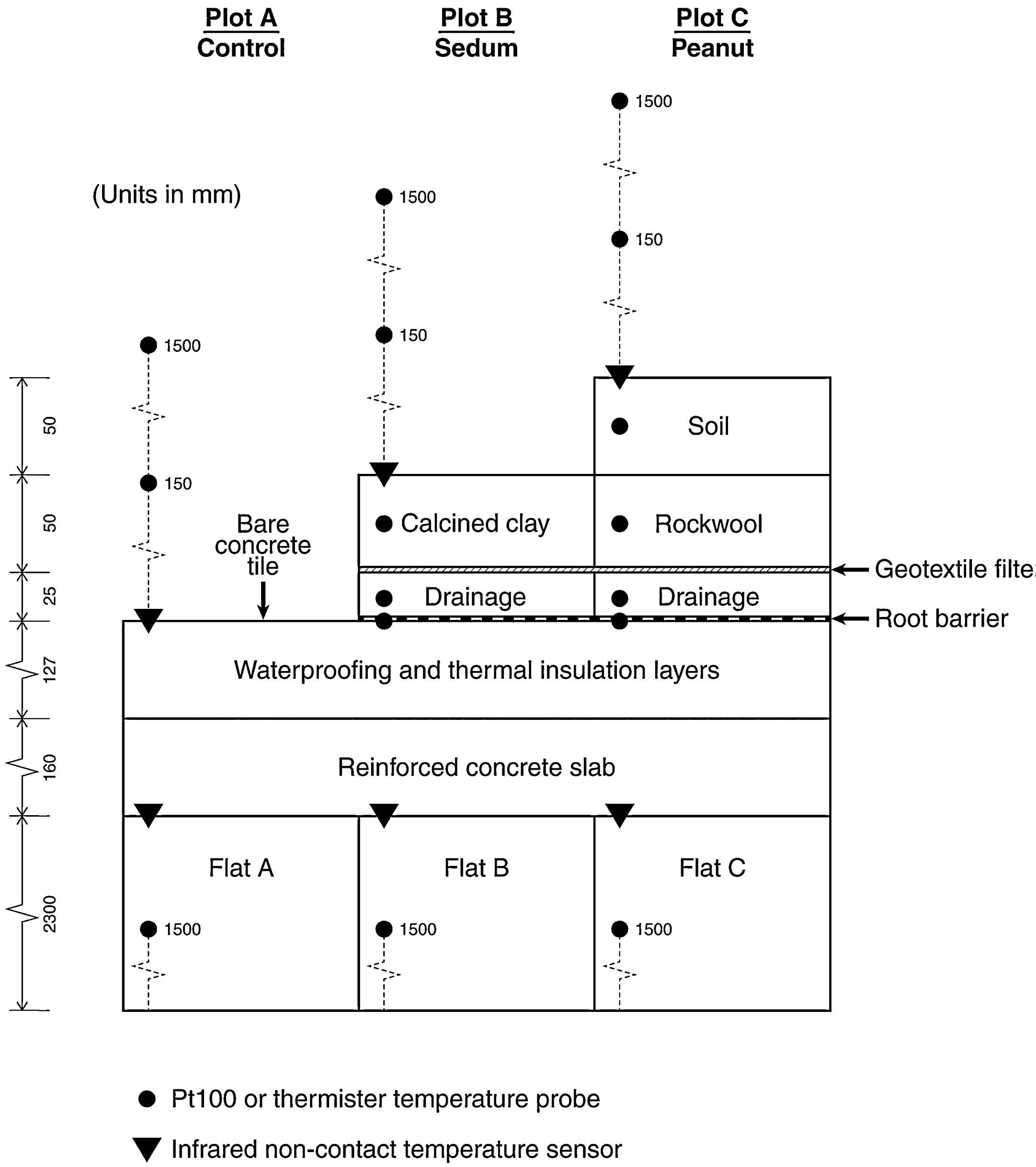

Fig. 3. The locations of temperature sensors installed at the three experimental plots along the holistic vertical profile that extends from the indoor through the roof slab to the green roof layers and outdoor positions.

wind speed, wind direction and rainfall (weather station, Hobo). Data loggers (Lufft, Fellbach, Germany) were programmed to acquire signals at 15-min interval and store them for periodic downloading to a notebook computer.

The large room (living room) in the three apartments was each equipped with a window-type air-conditioner (Model CW-XC1810EA, Panasonic, Osaka, Japan) with a cooling capacity of 5.13 kW (17,500 Btu/h), EER of 2.85 W/W, and air flow capacity of 13.3 m^3/min. The internal thermostat set the equilibrium temperature at 24 °C, which is a relatively high value strongly advocated by the government to achieve energy saving in the city. Setting it at a lower temperature would have resulted in higher energy consumption and hence apparently more significant energy saving of green roof. The energy-consumption data based on the relatively high temperature setting can therefore offer practical implications to the real-world situation. Moreover, by standardizing the indoor temperature, the experiment can reduce the effects of extraneous factors and focus squarely on the cardinal experimental treatment of green-roof types. They were connected to an electronic timer (CCT15852, Schneider, Rueil Malmaison, France), and a precision energy logger (A1700 Polyphase Energy Meter, Elster Metering Ltd., Luton, Bedfordshire, UK) to record electricity consumption in kWh unit. All windows and air-conditioner ventilators were kept closed to reduce external influence. The air-conditioners operated on 24-h cycles from midnight to midnight on sample days for different seasons and weather conditions. The small room (bedroom), not equipped with an air-conditioner, served as a baseline.

The green roofs were installed in March 2011 and were nurtured for seven months to establish a complete vegetation cover in the first growing season before live data collection was initiated. The sites were monitored for 12 consecutive months, from October 2011 to October 2012, to capture data for four seasons with three weather scenarios (sunny, cloudy and rainy).

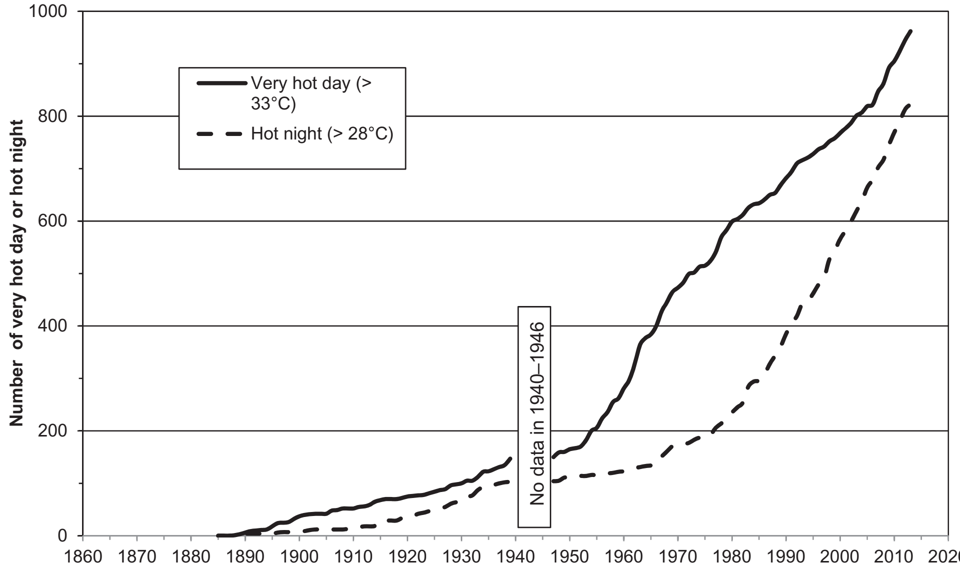

Fig. 4. Cumulative number of very hot days and hot nights from 1885 to 2013 recorded in Hong Kong.
Data source: Hong Kong Observatory (2013).

3. Results and discussion

3.1. UGS and energy consumption in Hong Kong

Hong Kong has a small area of merely 1108 km^2 which is constrained by a hilly rugged landform with limited flat and easily developable land. Since its inception in the 1840s, urban development mode has been predominantly high-density, with dense packing of buildings and roads and meager provision of interstitial open spaces or greenery. Subsequent urban expansion and internal renewal have brought further landuse intensification and infilling. The resulting ultra-compact and overwhelmingly vertical city concentrates built-up areas in only 24% (265.9 km^2) of the land (Planning Department, 2012), which accommodates the 7.18 million population (Census and Statistics Department, 2013). About 22.6% (60 km^2) were reclaimed from the sea at a high monetary and time cost (Lands Department, 1996).

In the tropical city, solar-heat absorption and artificial heat generation have accentuated the urban heat-island (UHI) effect which is superimposed on the global warming trend. Hot weather warning (maximum daily temperature above 33 °C) and hot-night phenomenon (nighttime temperature above 28 °C) are getting more frequent in recent years (Fig. 4). The warming trend is indicated by a gradual rise in annual mean temperature, from 0.12 °C/decade in 1885–2012, to 0.15 °C/decade in 1947–2012, and 0.22 °C/decade in 1983–2012 (Chan, Kok, & Lee, 2012; Hong Kong Observatory, 2013). The hot nights showed a statistically significant rising trend, whereas very hot days had less significant results (Lee, Chan, Ginn, & Wong, 2011). This result is corroborated by hot night occurrence which indicates a more notable increase than very hot days (Fig. 5). The elevated temperature has aggravated heat stress (Cheng, Ng, Chan, & Givoni, 2012) with health and mortality repercussions, and increased cooling energy consumption. It is necessary to adjust the urban fabric's thermal properties to ameliorate the UHI effect.

The compact city has extremely limited provision of public open spaces at 2.3% of the land area, translated into merely 3.55 m^2 per person, which is one of the lowest amongst cities of a comparable scale in the world. Similar compact cities in the region have notably better provision, such as Taipei with 5 m^2/capita, Singapore 7 m^2 and Guangzhou 10 m^2 (Chen & Jim, 2011). The UGS-deficit is aggravated by extensive (commonly more than half) hard paving

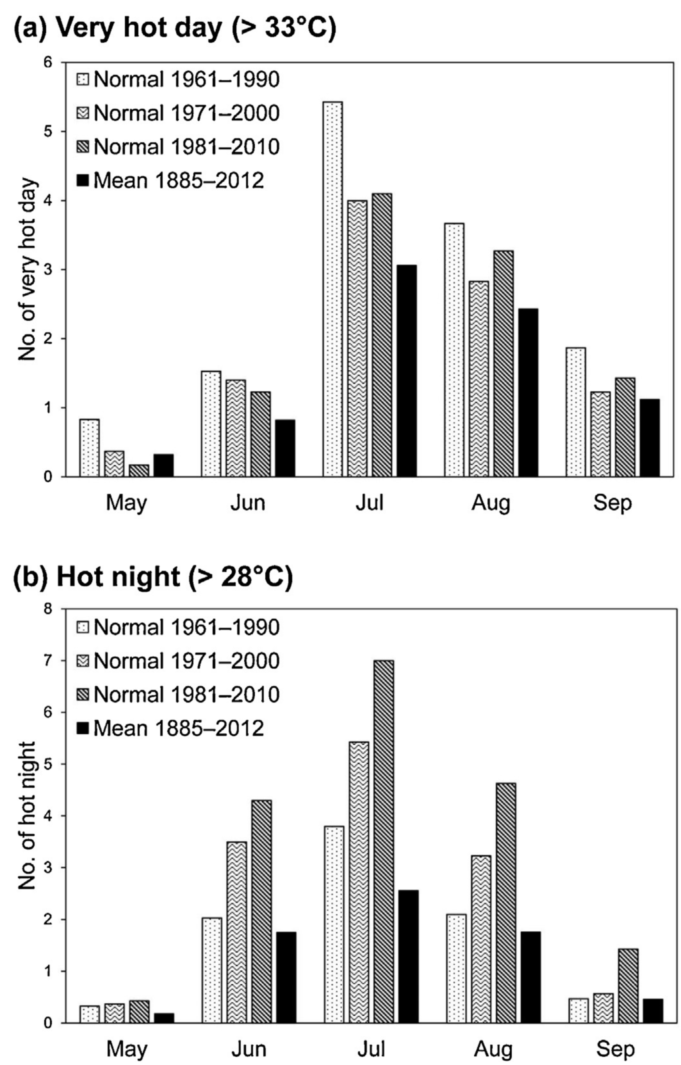

Fig. 5. Trends of climatological normal and mean of the number of (a) very hot days and (b) hot nights in Hong Kong.
Data source: Hong Kong Observatory (2013).

of open spaces. Due to the rigid town plan and lack of enabling policy, the inherent deficiency of ground-level UGS has slim prospect of improvement. However, the vertical city has plenty of bare rooftops available for greenery infilling (Tian & Jim, 2011, 2012). The wasted spaces absorb an appreciable amount of solar radiation in the extended warm season to significantly raise energy use for air-conditioning (Jim & Peng, 2012). The green roof innovation can reverse the role of solar energy in imposing an inordinate thermal load. Instead, solar radiation can be harnessed productively and proactively to take heat away through evapotranspiration. In addition, shading and thermal insulation by green roof layers can reduce heat flux into indoor space. The increase in albedo due to green roof vegetation, in companion with conventional barren roof surfaces, can also reduce solar heat absorption by the building fabric (Castleton et al., 2010). Common installation of green roofs in cities could bring appreciable aggregate cooling and energy-conservation benefits.

In 2011, 63% of the energy use in Hong Kong is consumed in commercial and residential buildings. In the residential sector, 23% (13,188 TJ) were used for space air-conditioning, and in the commercial sector, 26% (30,227 TJ) (Electrical and Mechanical Services Department, 2013). Including the public transport sector, air-conditioning alone consumes about one-third of the electrical energy generated by fossil fuel combustion (Environmental Protection Department, 2013). The long hot-humid summer period incurs a heavy energy burden on the city (Lee, Kok, & Chan, 2010), inducing upstream impingement on air quality and greenhouse gas emission at power plants (Tso & Yau, 2003).

Most building envelopes in Hong Kong suffer from poor thermal insulation, resulting in wasteful use of air-conditioning energy (Bojić & Yik, 2005; Bojić, Yik, & Leung, 2002). On hot days, building cooling load could be burdened by ready penetration of ambient heat into indoor space and leaking of cooled indoor air to the external environment. Thermal insulation of buildings in the humid-tropical city has much room for improvement in the interest of energy conservation. Climate change is likely to increase the demand for air-conditioning energy (Lam, Wan, Wong, & Lam, 2010). Modern technology and living vegetation in the form of green roofs and green walls could be employed to reinforce shielding of building envelopes to bring energy savings (Jim, 2015a, 2015b).

3.2. Characteristics and behavior of experimental plots

Analysis of the monitoring data highlighted the prominent cooling effect in summer. The following sections focus on this season with the help of diurnal temperature variations of sunny, cloudy and rainy sample days. The results of the Control, Sedum and Peanut plots are shown, respectively, in Figs. 6–8. Air-conditioning electrical energy consumption data are plotted in Fig. 9.

The Control plot presented the worst-case scenario, with bare concrete tiles fully exposed to the elements. Solar radiation could strike the roof materials directly to heat them up in daytime. The heat can be stored and transferred to adjacent air above the roof and through the roof slab to underlying indoor space. On rainy days, rainwater can reach and cool the surface tiles directly.

The Sedum plot denoted a basic form of green roof with minimum material layers, substrate thickness and vegetation biomass and structure. The CAM succulent plant had limited transpiration and corollary cooling effect in comparison with broadleaved groundcover plants. The experiment probed the extent to which such a simple green-roof could bring cooling benefits.

The Peanut green roof represented a more complex design with full complement of material layers. The multiple and thicker strata may provide more effective insulation to reduce solar-heat passage into interior space. Moreover, Peanut plants could maintain a full and vigorous cover throughout the study period.

3.3. Thermal effect on summer sunny day at Control plot (Fig. 6a)

The Control plot on the long summer sunny day echoed the intensive tropical solar radiation. With massive heat absorption, the thermal regime denoted the worst-case scenario for a tropical rooftop. The maximum roof surface temperature rose to 41.5 °C, above the ambient maximum of 38.6 °C. The heat retained by roof materials partly shifted upwards by convection to near-ground air, which was warmed notably at 15 cm with a somewhat reduced effect at 150 cm.

The upward passage of sensible heat by the heated bare roof indicated the thermal burden imposed by numerous bare roofs in Hong Kong on urban climate. At the low 15 cm level, air temperature was raised to 40.6 °C, and at 150 cm to 38.6 °C. The densely packed buildings and roads in the urban fabric, dominated by artificial materials with high thermal capacity, could collectively retain a significant amount of heat to warm the city's air. Thus this heat-transfer pathway contributed to the city's aggravating urban heat island (UHI) effect.

The solar energy began to warm the roof surface from sunrise, reaching a conspicuous peak shortly after midday, and ending by sunset. The heat stored in the roof materials took time to release to the atmosphere. Thus the air-warming effect continued well beyond the evening and extended to nighttime. This nighttime warming contributes to the undesirable hot-night phenomenon in urban climate (Hong Kong Observatory, 2013). In recent years, the city has experienced continual increase in hot nights (Figs. 4 and 5; Cheng et al., 2012), with implications on human comfort, human health, and electricity consumption. The latter could induce an upstream environmental backlash at power plants.

Heat absorbed by the bare roof also transmitted downwards to the interior space lying underneath. The insulation layers in the roof slab retarded and reduced downward heat flux but some heat managed to get through. Despite sharp temperature rise and fall in the 24-h cycle, indoor air and ceiling temperature remained rather stable. The enclosed indoor space with physical and thermal shielding by roof slab and walls, was strongly regulated by building-fabric buffering effect. The diurnal indoor air temperature fluctuation was compressed to a circa-1 °C narrow range.

The indoor air temperature of the small room (not air-conditioned) at 28.4–29.2 °C, stayed above the minimum ambient temperature of 27.6 °C. The maintenance of warm indoor air from morning till midnight reflected an extended transmission of heat from roof to indoor environment. This continual heat ingress throughout the day incurred a sizeable cooling load on indoor space. Residents are likely to use air-conditioners to lift energy consumption and impose a long-term energy burden. This human response to the warmed interior space could incur chronic economic and environmental costs on the community. If the roofs are vegetated, this load could be partly relieved.

3.4. Thermal effect on summer cloudy and rainy days at Control plot (Fig. 6b and c)

Summer cloudy day presented a markedly different picture. Subdued solar radiation suppressed midday temperature peaks in the outdoor environment. Both outdoor and indoor temperatures registered limited ranges within the day. Temperature difference between the 15 and 150 cm levels disappeared, and roof surface temperature dropped notably below them. Outdoor temperatures were getting close to indoor air temperature. Reduction in radiative cooling kept outdoor air and surface temperatures high at night. The whole-day heat passage from roof to indoor space sustained

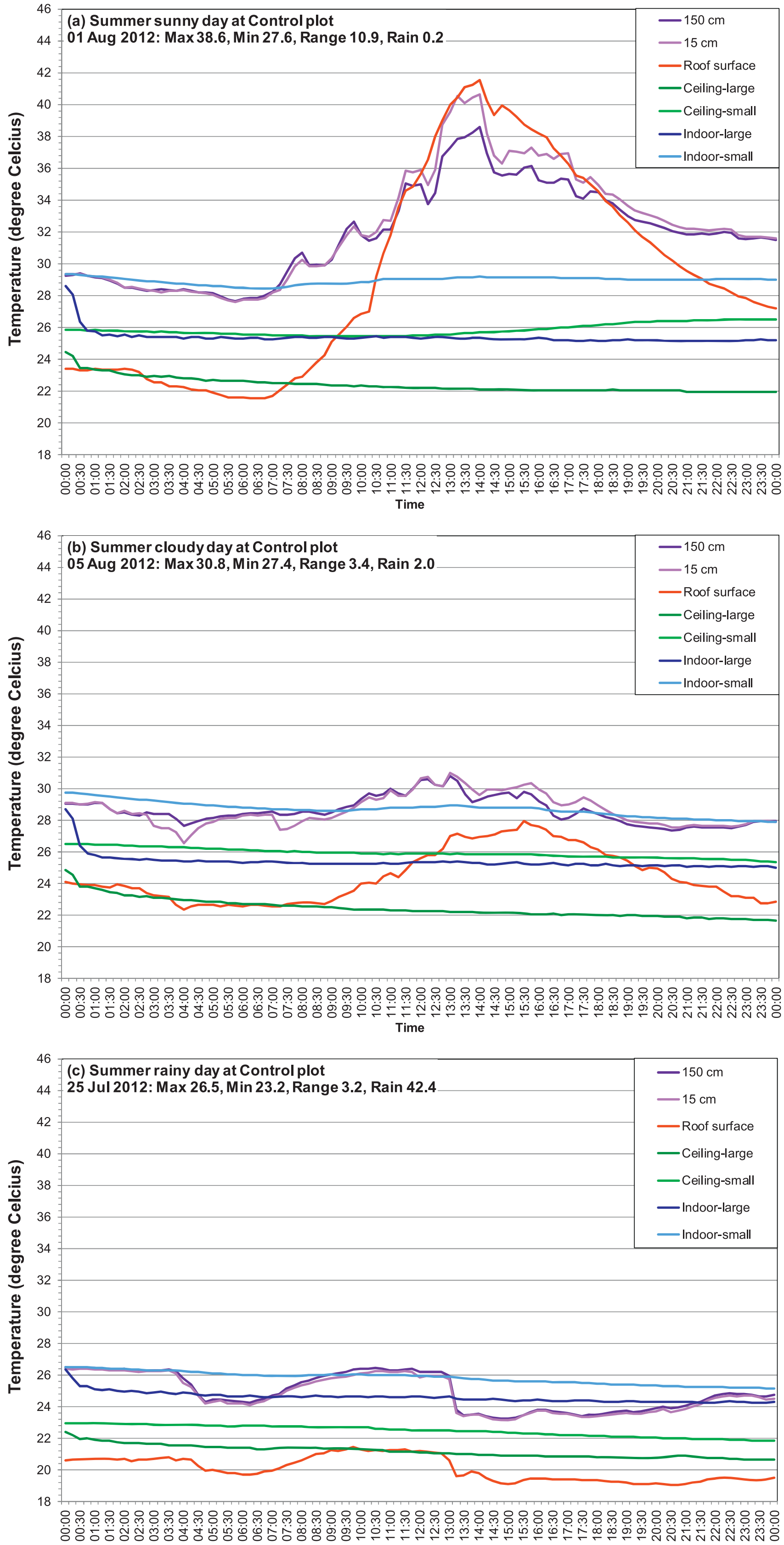

Fig. 6. Diurnal cycle of outdoor, green roof and indoor temperatures at the Control plot, respectively, on: (a) summer sunny day; (b) summer cloudy day; and (c) summer rainy day.

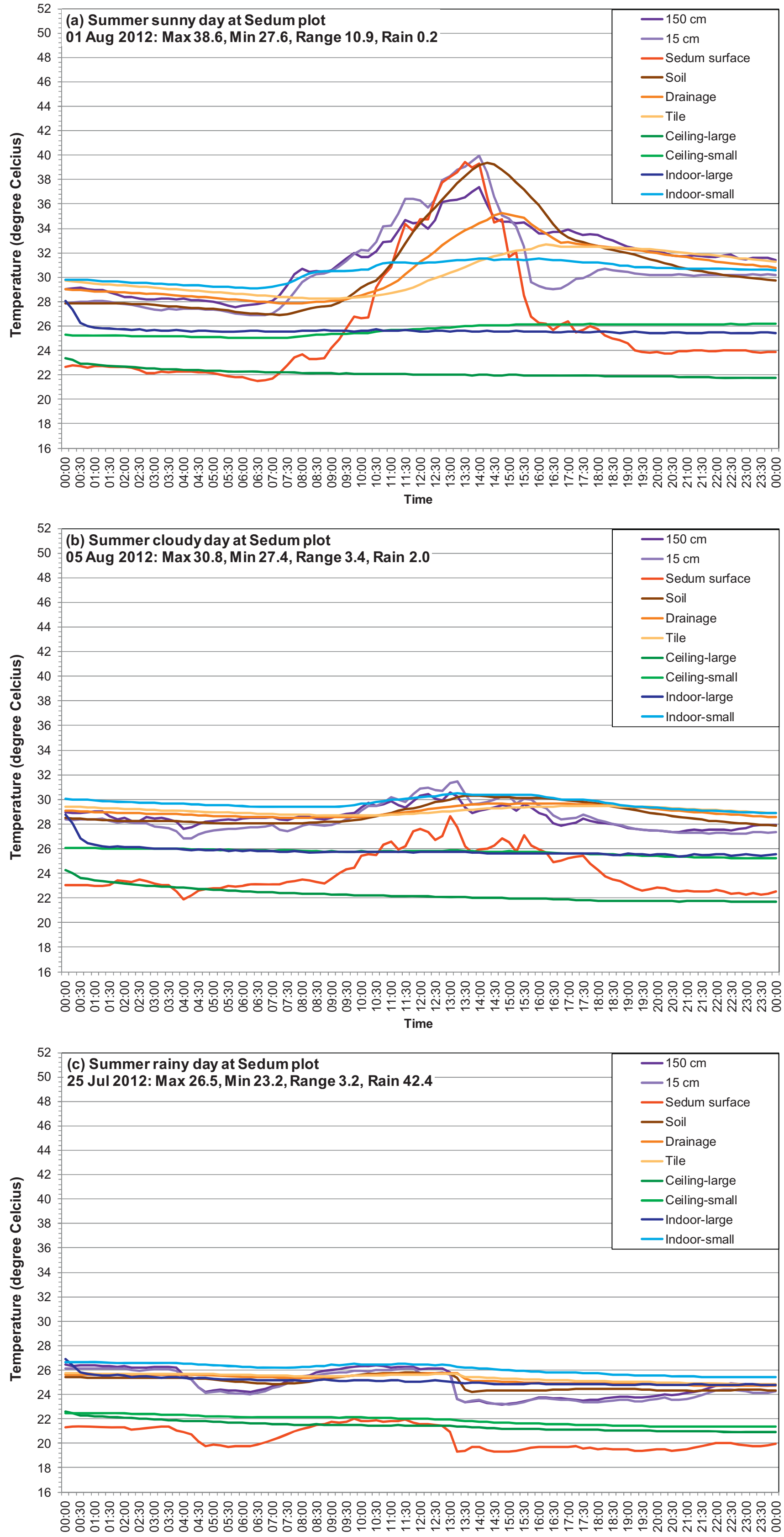

Fig. 7. Diurnal cycle of outdoor, green roof and indoor temperatures at the Sedum plot, respectively, on: (a) summer sunny day; (b) summer cloudy day; and (c) summer rainy day.

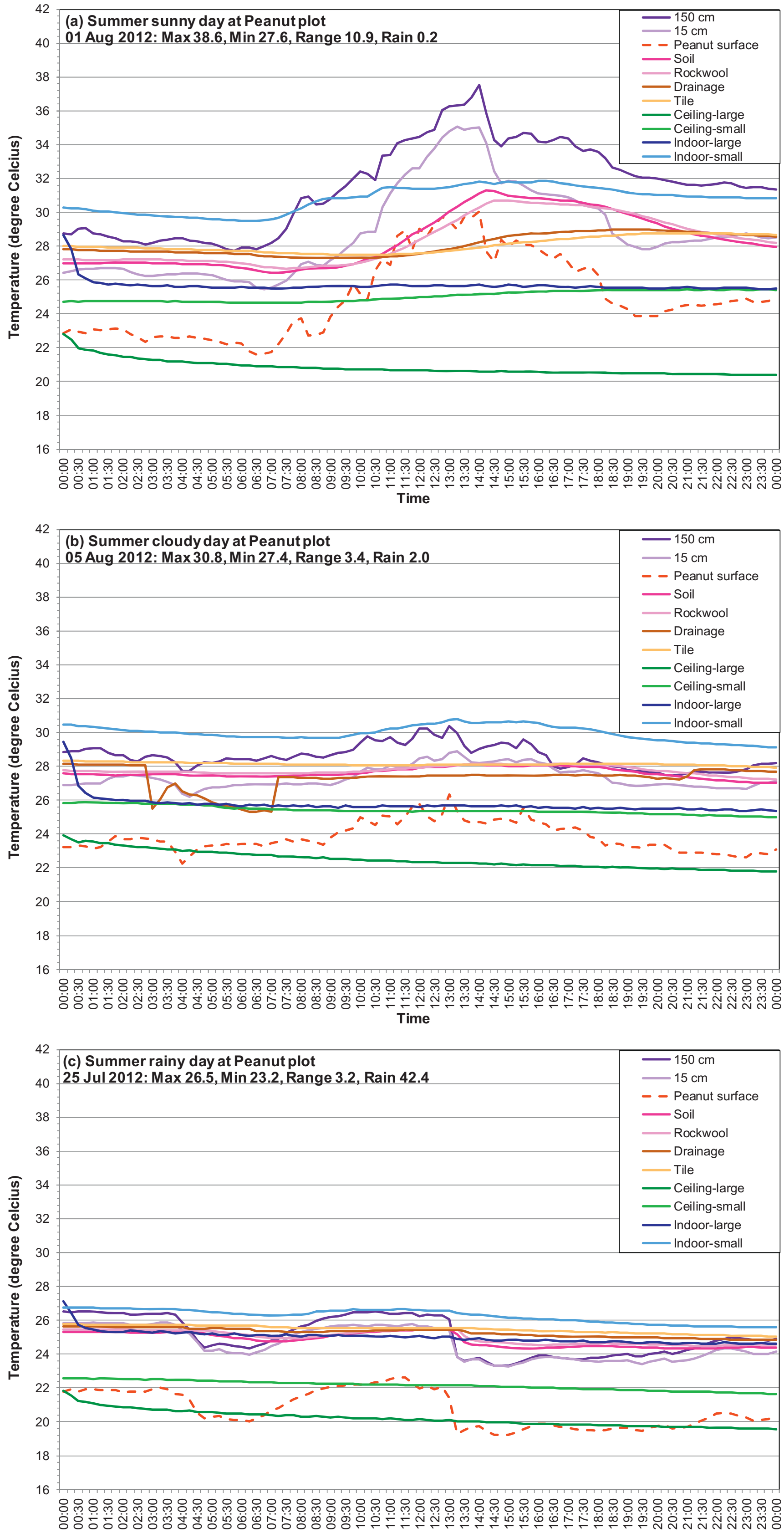

Fig. 8. Diurnal cycle of outdoor, green roof and indoor temperatures at the Peanut plot, respectively, on: (a) summer sunny day; (b) summer cloudy day; and (c) summer rainy day (temperature in °C and rainfall in mm).

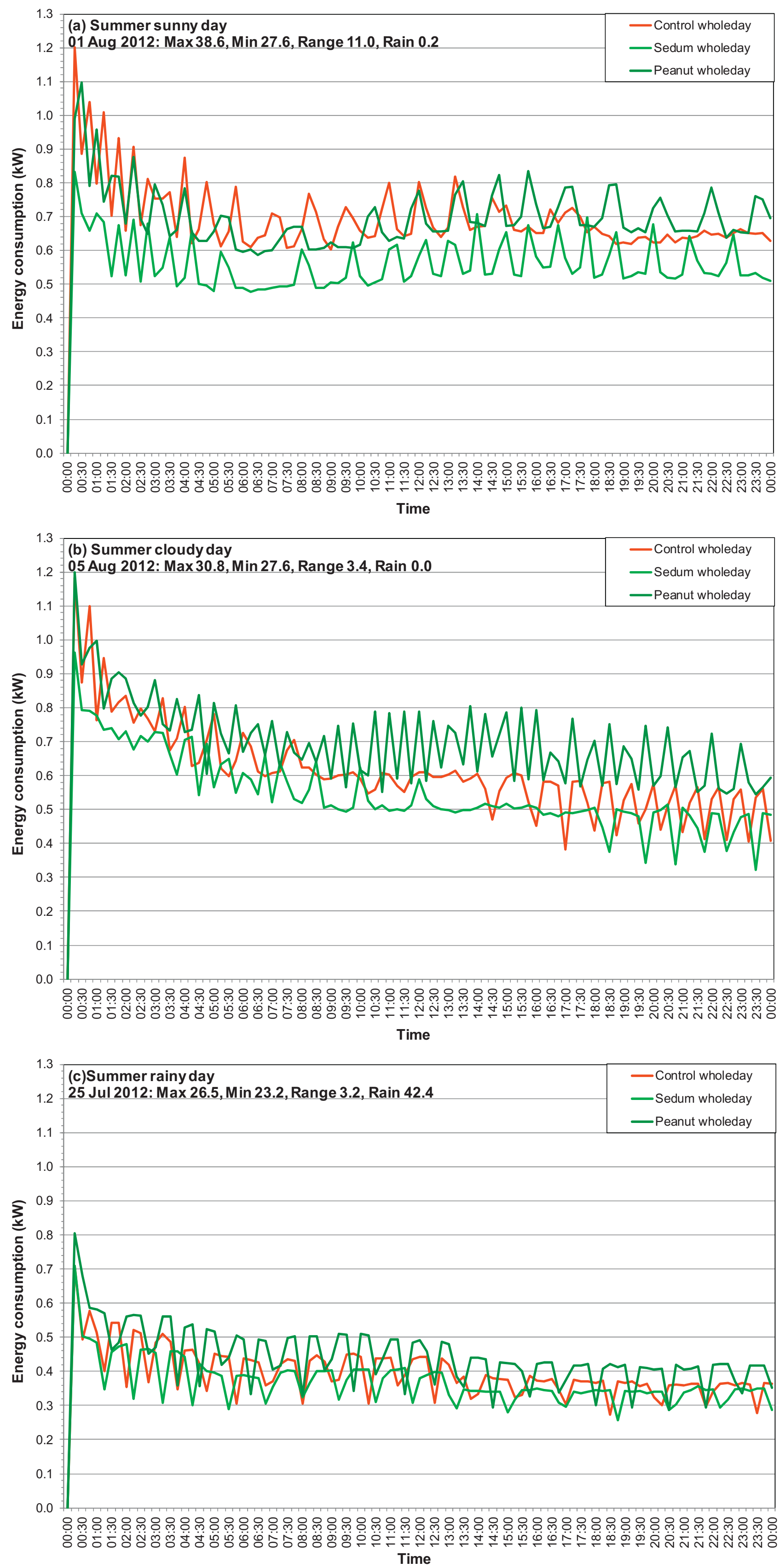

Fig. 9. Diurnal cycle of air-conditioning electricity energy consumption of the flats below the three experimental plots, respectively, on: (a) summer sunny day; (b) summer cloudy day; and (c) summer rainy day (temperature in °C and rainfall in mm).

relatively high indoor air temperature at around 28.9 °C which lied between the ambient maximum and minimum.

Summer rainy day had significant reduction of solar energy input, more so than summer cloudy day, to depress both air and material temperatures at the roof. Cooling was accentuated by rainwater. Roof surface temperature was markedly depressed to the coolest amongst all sensors. Outdoor air temperatures were lowered, and the differences between outdoor and indoor air temperatures diminished. The amount of heat moving into indoor space was drastically curtailed. The stored heat in roof slab and building fabric (building buffering effect) maintained indoor temperature at around 26 °C to lie between ambient maximum and the minimum.

3.5. *Thermal effect on summer sunny day at Sedum plot (Fig. 7a)*

On summer sunny day, the Sedum green roof recorded maximum temperatures of 39.4 °C at vegetation surface and 40.0 °C at 15 cm, which were slightly lower than Control. It indicated the limited ability of the living vegetation to cool down its own tissues. The unusually warm Sedum surface could be attributed to stomata closure of the CAM plant under the hot sun that suppressed transpiration cooling (Stephenson, 1994).

At night, the Sedum surface cooled down rapidly to reach the lowest temperature amongst the sensors. Nighttime opening of stomata in relation to CAM photosynthetic physiology to take in and store carbon could have contributed to this cooling. Plant tissues thus aerated at night could experience facilitated cooling. Thus Sedum tissues had a limited temperature buffering capacity, tending toward high daytime maximum and low nighttime minimum.

The Sedum substrate was heated to a maximum of 39.4 °C, same as vegetation surface. The incomplete Sedum cover in summer permitted solar radiation to heat up the exposed substrate. The shielding effect of Sedum on substrate was partly offset by poor plant growth in summer. Some of the substrate heat passed downwards to warm drainage layer and tile (green roof bottom) (Jim & Tsang, 2011b). These two subsurface materials reached a maximum of, respectively, 35.3 °C and 32.6 °C in afternoon, and the warmth was sustained well into the night. In turn, some of this subsurface heat moved downwards to warm indoor air.

Despite Sedum green roof installation, the indoor temperature remained rather high at a maximum of 31.6 °C, which was warmer than Control. The simple green roof did not significantly reduce heat ingress into indoor space. The warmed substrate created a weak heat-sink effect to generate downward heat transmission.

3.6. *Thermal effect on summer cloudy and rainy days at Sedum plot (Fig. 7b and c)*

In comparison with summer sunny day, reduction in solar energy input on summer cloudy day noticeably dampened outdoor air (maximum at 31.5 °C at 15 cm and 30.5 °C at 150 cm) and Sedum surface (maximum at 28.6 °C) temperatures. The effect was similar to Control plot on the same sample day. Indoor air temperature remained relatively high at a maximum of 30.5 °C, but slightly above summer sunny day to contribute to cooling load.

On summer rainy day, the Sedum green roof presented comparable temperatures at outdoor air and materials and indoor air. The weather condition brought convergence of temperatures at different sensor locations. Sedum surface temperature presented the odd one with notably cooler tissues throughout the day to reflect lower solar radiation input and effective cooling by rainwater, which echoed their limited temperature buffering capacity. The rainy day cooled outdoor air and material temperatures, which in turn trimmed heat passage to indoor space.

3.7. *Thermal effect on summer sunny day at Peanut plot (Fig. 8a)*

The Peanut plot on summer sunny day behaved in some ways similar to Sedum plot, but with more pronounced outdoor cooling effect. The maximum outdoor air temperature was 37.5 °C at 150 cm in comparison with 40.6 °C at 15 cm of Control and 40.0 °C at 15 cm of Sedum. The vertical temperature profile in daytime demonstrated an anomaly in the form of a temperature inversion (temperature increase with height). The temperature ranking was 150 cm (37.5 °C) > 15 cm (35.0 °C) > Peanut surface (31.3 °C). This phenomenon indicated the effective cooling from below by evapotranspiration from the green-roof soil and vegetation. Control and Sedum roofs did not express vividly this evapotranspiration cooling.

Soil and rockwool layers were heated up, but to a lesser extent than Sedum. Warming of drainage and tile layers was more subdued than Sedum. Such results signified that Peanut vegetation formed an efficient living blanket on soil surface to shield underlying soil from direct solar radiation. Peanut surface registered a maximum temperature of 31.3 °C, in comparison with 39.4 °C at Sedum surface, denoting a more powerful passive cooling mechanism.

Similar to the Sedum scenario, the indoor air temperature (small room) at the Peanut plot rose in the morning and maintained the elevated temperature (maximum at 31.9 °C versus ambient maximum of 38.6 °C) thereafter until midnight. It was noticeable to have sustained warmth in the indoor environment, which could be explained by the higher thermal capacity of Peanut green roof. The substrate composed of mineral–organic soil mix and the additional rockwool layer jointly provided a thicker layer with higher water-holding capacity. With enhanced thermal capacity, the substrate could store more heat which in turn could allow more heat to transmit downwards. Thus the benefit of a full and pleasant green cover at the Peanut plot was partly offset by more heat passage from green roof to indoor space.

3.8. *Thermal effect on summer cloudy and rainy days at Peanut plot (Fig. 8b and c)*

On summer cloudy day, the Peanut plot's diurnal temperature pattern was similar to Sedum. Peanut air and surface were slightly cooler than Sedum. Again, a temperature inversion had developed from the vegetation surface upwards, expressing cooling of air adjoining the green roof. This vertical temperature profile corroborated with the summer sunny day scenario, indicating that Peanut green roof was more efficient in passive cooling of air by evapotranspiration from soil and vegetation.

However, the indoor (small room) air temperature at Peanut roof is consistently higher than Sedum roof. Its maximum temperature of 30.8 °C was the highest amongst all sensor positions. The heat retained by water in substrate and rockwool layers created a pronounced heat sink to push more heat downwards into indoor space. This notable indoor warming imposed an appreciable cooling load.

On summer rainy day, the Peanut plot again depicted a daily temperature pattern analogous to Sedum. The temperature inversion was also expressed at the Peanut plot with a subdued thermal gradient. It indicated that evapotranspiration cooling effect of the green roof continued to operate even on rainy day, but with stifled efficiency. The indoor temperature was similar to Sedum throughout the day, again indicating imposition of a cooling load.

3.9. *Air-conditioning energy consumption on summer sunny day (Fig. 9a and Table 2)*

The initial start-up boost shot up to conspicuous energy consumption spike for the three flats, and dropped sharply thereafter.

Table 2
Daily air-conditioner electricity consumption and compressor on-off cycle on three summer sample days.

Weather	Date (yyyymmdd)	Value by plot (kW or no.)				Comparison with Control (%)		
		Control	Sedum	Peanut	Total	S–C	P–C	S–P
(a) Daily electricity energy consumption (kW)								
Summer sunny	20120801	67.02	54.00	67.16	188.18	−19.42	0.21	−19.64
Summer cloudy	20120805	58.83	52.61	67.27	178.71	−10.58	14.35	−24.9
Summer rainy	20120725	38.15	35.39	42.46	116.00	−7.23	11.31	−18.53
Total		163.99	142.00	176.89		−37.23	25.87	−63.10
(b) Daily air-conditioner compressor on–off cycle (no.)								
Summer sunny	20120801	17	22	18	57	29.41	5.88	23.53
Summer cloudy	20120805	21	17	35	73	−19.05	66.67	−85.71
Summer rainy	20120725	21	17	23	61	−19.05	9.52	−28.57
Total		59	56	76		−8.68	82.07	−90.76

In the early part of the day, the on–off cycles in compressor operation displayed a high frequency, which was more so for Control flat and less so for vegetated flats. Before noon, the Control flat had the highest the energy consumption, but in the afternoon from about 1415 h it was replaced by Peanut. The diurnal amplitude of energy consumption, excluding the early boost, spanned mainly from 0.5 to 0.8 kW. The increase in energy consumption in the afternoon for all three curves showed only a small bulge in comparison with conspicuous outdoor temperature peaks on summer sunny day.

The daily energy consumption patterns demonstrated affinities between the Control and Peanut flats. The energy consumption at the Sedum flat was consistently the lowest throughout the day, at around 0.1–0.2 kW below the Control and Peanut flats. Peanut had the highest total daily energy consumption at 67.16 kW which is slightly higher than Control at 67.02 kW; Sedum registered a notably lower figure of 54.00 kW. By compression cycles, Peanut has the highest value, followed by Sedum and control.

The hot summer sunny day pushed the ambient maximum to 38.6 °C and minimum to 27.6 °C. A proportion of the solar heat absorbed by bare and green roofs passed downwards to generate a cooling load in indoor space. The sharp rise in energy consumption at the beginning of the experimental cycle indicated that need to bring the rather hot room temperature down to equilibrium level. This was necessary despite the relatively lower indoor temperature from midnight to sunrise.

The rather high frequency and relatively wide amplitude of on–off cycles signified that the air-conditioners have to work strenuously to reach equilibrium temperature. This was especially true of Control and the Peanut flats than Sedum. The wide pre-dawn trough at Sedum and Peanut flats indicated that indoor air was cooled effectively to reach equilibrium level whilst solar input had not started yet.

The Control and Peanut flats used more energy than the Sedum flat. Their energy consumption profiles, however, varied within the sample day. From midnight to about noon, Control flat consumed more energy to attain the equilibrium temperature. The pattern indicated that Control flat experienced a higher temperature early in the sample day. In the afternoon, the pattern was reverse, with the Peanut flat drawing more energy to reach equilibrium temperature. This trend indicated that the Peanut plot had absorbed and stored an appreciable amount of heat, a part of which was transmitted downwards to generate a cooling load.

The higher energy consumption of Peanut flat was sustained from noon through sunset to midnight. This behavior echoed its heat-sink effect, and extended residual heating of underlying indoor space. The heat absorbed in daytime continued to stream downwards to warm indoor air to demand cooling energy. On the hot summer sunny day, the Peanut green roof pushed heat downwards to raise energy consumption, which contradicted common belief of cooling benefit.

It was somewhat unexpected that Sedum flat carried a lower cooling load than Peanut throughout the sample day. The Sedum plant lost its full cover in summer due to plentiful rainfall. However, its pottery-pellet substrate and the absence of rockwool layer had limited water-holding capacity, hence limited thermal capacity. With reduced heat gain in daytime and efficient heat dissipation in nighttime, Sedum plot did not generate a notable heat sink. As a result, Sedum flat required less energy to reach equilibrium temperature.

The Peanut plot achieved and maintained an excellent plant cover soon after planting. The dense foliage and effective transpiration, however, could not dampen warming of its green-roof materials. The high ambient temperature triggered a high transpiration rate and significant absorption of latent heat of vaporization. Nevertheless, the domain of evapotranspiration cooling mainly extended upwards to benefit the near-ground air, but it brought little downward cooling to the substrate. Evapotranspiration cooling was decidedly unidirectional and upwards. Peanut plot continued to impose a high cooling load to the underlying apartment. This phenomenon indicated the key role played by substrate moisture in governing thermal regime of indoor space and cooling load.

The apparent anomaly could be explained by inherent differences in green-roof design between Peanut and Sedum roofs. The Peanut plot had thicker substrate plus rockwool layers, whereas Sedum had only porous pottery pellets without underlying rockwool. Thus Peanut green roof had a significantly higher water-holding capacity than Sedum. The compositional difference led to divergence in hydrological and thermal property and behavior. Peanut was augmented by ample constituent pore water with considerable thermal capacity to play the effective heat-sink role. The stored heat sustained more heat flux to indoor space, with a magnitude exceeding Control plot.

3.10. Air-conditioning energy consumption on summer cloudy and rainy days (Fig. 9b and c; Table 2)

Peanut recorded the highest daily energy consumption of 67.27 kW, which was slightly higher than sunny day. It is followed by 58.53 kW of Control, and 52.61 kW of Sedum. Peanut also had the largest number of on–off compressor cycles at 35, followed by 21 at Control and 17 at Sedum.

Besides a brief period after the starting time, Peanut flat maintained the highest energy consumption throughout the day. In comparison with Control and Sedum, energy consumption at Peanut flat showed pronounced increase in early morning from 0900 h, characterized by more frequent on–off cycles as well as wider amplitude between troughs and peaks. The pattern persisted all the way to midnight, with a small reduction after sunset. Energy consumption at Control flat maintained a middle rank throughout the day, with a small and progressive decline after sunset. Sedum flat kept the lowest energy use throughout the day, with notable reduction from afternoon to sunset.

Overall, the three curves demonstrated increasingly divergent daily trends in energy consumption. Their differences were smaller before sunrise, and progressively widened toward midnight. The diurnal amplitude of energy consumption, excluding the early boost, spanned a relatively wide range from about 0.4 to 0.8 kW.

In comparison with summer sunny scenario, summer cloudy day delivered less solar energy to the roof systems. The maximum ambient temperature attained 30.8 °C and minimum 27.4 °C. Conversion of solar radiation to stored sensible heat in the green roof materials proceeded apace in Peanut plot. This phenomenon signified operation of heat-sink effect as explained in Section 3.4(a). It also indicated the effective blanket effect of the dense foliage to retard heat loss from material layers by radiative cooling and convection.

The antecedent heat Peanut green roof partly accounted for the relatively high cooling load on the sample day. Some of the heat accumulated in its materials was acquired on previous days. With continuous hot days without rainfall, heat storage and hence temperature could climb up progressively to develop thermal inertia. The cooler Sedum flat and reduced energy need could be attributed to lower moisture and heat storage capacity of its substrate, as explained in Section 3.4(a).

Thus on summer cloudy day, despite Peanut's luxuriant growth and high coverage, it drove higher indoor temperature to demand more cooling energy. It is noticeable that the energy need of Peanut exceeded the Control flat.

For the summer rainy day, after an initial start-up boost in energy consumption in three flats, it declined at a slow rate toward midnight. Throughout the day, the Peanut flat sustained consistently the highest energy consumption, followed by Control and then Sedum. All three flats recorded notable reduction in daily energy consumption, but Peanut maintained the highest rank at 42.46 kW, followed by Control at 38.15 kW and Sedum at 35.39 kW. The compressor on–off cycles had the same sequence, with Peanut achieving 23 times, followed by Control 21 times and Sedum 17 times.

The differences amongst the three curves became progressively smaller from beginning to end of the sample day. The peaks of the on–off cycles switched from narrow-sharp to broad-flattish from about 1330 h onwards, which coincided with reduced energy use. The diurnal amplitude of energy consumption, excluding the early boost, spanned a relatively narrow range from about 0.3 to 0.5 kW before 1330 h, and thereafter shrinking to about 0.3–0.4 kW.

The subdued solar-energy input on summer rainy day reduced energy acquisition by roof plots. Roof surface and material cooling were accentuated by rainwater which amounted to 42.4 mm on the sample day. Cooling at the roofs suppressed the thermal gradient, which in turn trimmed downward heat flux to indoor space. The resulting indoor cooling notably shaved the energy required to attain equilibrium temperature. As maximum ambient temperature was 26.5 °C and minimum 23.2 °C, it did not need much energy to reach the target.

The lower ambient and indoor temperatures also shrank the differences in energy consumption amongst the three flats. The amplitude of on–off cycles, besides the initial boost, was confined to about 0.2 kW, which was further reduced to about 0.13 kW from 1330 h onwards. Rainfall occurred on and off throughout the day, peaking at 1315 h with 13.20 mm. Delayed rainwater indoor cooling (DRIC) was expressed, as indicated by the evident stepping-down of energy use at around 1330 h.

4. Implications and conclusion

This study evaluated vegetation effect on green roof thermal-energy performance with reference to climate adaptation in the compact tropical city of Hong Kong. From the findings, practical recommendations have been distilled to inform design, installation and maintenance of a simple, durable and low-maintenance green roof on building rooftops in humid-tropical cities (Table 3).

In the tropics, the high intensity and duration of solar input especially in summer heats up the bare (Control) roof to a high temperature. The heat stored in the roof fabric creates a heat sink which in turn passes upwards to warm the ambient air and downwards to warm indoor space. The generation of sensible heat contributes to the UHI effect and air-conditioning energy consumption, with consequential upstream impacts at power plants and downstream impacts on human comfort and health. The common roof-slab thermal insulation layers could retard or reduce but could not stop heat ingress from roof to indoor space. The massive heat gain by buildings and artificial surfaces in summer calls for innovative, sustainable and cost-effective solutions to enhance climate adaptation in cities.

The Sedum green roof lost some of its cover in hot-wet summer when its shading and cooling effects were earnestly needed. With an inherently low rate of transpiration which could be shut down under high temperature and water stress conditions (CAM physiology), its contribution to transpiration cooling is limited. The thin substrate with limited water-storage capacity has limited influence on evaporation cooling. As a result, the Sedum roof warms the near-ground air similar to Control roof to contribute to UHI effect. Moreover, the heat absorbed at the green roof surface is partly transmitted downwards to warm subsurface layers and indoor space to raise the cooling load. However, the limited thermal capacity of the Sedum green roof could only generate a feeble heat-sink effect to incur restricted indoor warming.

A green roof with a good foliage cover and relatively high transpiration rate (C3 physiology) can contribute considerably to air cooling near the ground. The Perennial Peanut in the study can meet this condition, bringing an anomalous temperature inversion with air temperature increasing with height or decreasing toward the green roof vegetation surface (Table 3). The Peanut surface is cooled down significantly by daytime active transpiration, which in turn cools collaterally the near-ground air. The higher-level air is slightly cooled to fall a little below the ambient maximum. The dense foliage cover, however, creates an effective blanket to reduce evaporation from the substrate. The evapotranspiration cooling is thus decidedly unidirectional that works upwards but not downwards.

The Peanut green roof stores a significant amount of heat in its substrate and rockwool layers. The porous media with high water-storage capacity induces an appreciable thermal capacity or thermal mass to build a notable heat-sink effect. The heat fluxes downwards to warm indoor air and lift its cooling load. Its electricity consumption has been driven to a high level to exceed the Control under sunny, cloudy and rainy weather scenarios. The benefit of evapotranspiration cooling above the green roof has been partly offset by heat ingress into the building.

The Sedum green roof has the advantage of a simple design and passing less heat down to indoor environment. However, its poor growth in summer rules out widespread use in the tropics. The thermal performance of Peanut green roof is ambivalent. Its application demands design refinement to improve thermal performance and suppress shortcomings. It has the fine quality of notable air cooling, vigorous growth, full foliage cover with elevated albedo, active transpiration under hot summer conditions, and freedom from pests and diseases. If its heat-sink effect could be dampened, it can offer an optimal climate-adaptation solution. The green roof

Table 3
Condensed summary of practical recommendations for green roof design and maintenance in tropical cities.

	Issue	Practical recommendation
1	Choice of species	Based on the results of this study, Peanut has been found to perform significantly better than Sedum in terms of growth vigor, fast establishment, maintenance of a lush-green, dense and full foliage cover throughout the year, attractive golden-yellow flowers for six months in a year, nitrogen-fixing capability, attraction to wildlife (butterflies and bees), relatively free from pest and disease problems, not setting fruits outside the native geographical range (hence no worry of becoming garden escapes in ruderal sites), and ease of maintenance. Based on future research findings, other species could be added to the planting palette in due course
2	Substrate layer	A 5 cm layer of soil composed of completely decomposed granite amended with 20% (v/v) fully mature compost and slow-release fertilizer is suitable for Peanut growth. If roof loading is sufficient, the rockwool layer can be replaced by increasing the soil depth to 10 cm[a] to compensate for the loss in soil moisture storage capacity and rooting room. To adopt the thicker soil option, the roof slab should be strong enough to support the additional weight. For buildings that are yet to be constructed, the required loading capacity could be provided in the roof slab. For existing buildings, the loading capacity has to be checked to make sure that it can bear the extra weight
3	Rockwool layer	The rockwool layer has the benefit of light weight and an exceptionally high water storage capacity which can enhance water supply to green-roof plants. As a result, the thickness of the soil layer, which is the heaviest of all green-roof materials, could be correspondingly reduced. However, the research findings highlighted the retention of heat in the moisture stored in the rockwool material to create a heat sink, which can induce heat transmission downwards to raise the cooling load of indoor air. As explained above, this layer can be deleted but it has to be compensated by increasing the soil thickness
4	Filter layer	This layer must be present to prevent soil particles, especially fine ones, from entering the drainage layer to reduce its water-shedding efficiency
5	Drainage layer	This layer must be present to drain quickly the water released by the soil and rockwool layers away from the green roof site so as to prevent waterlogging. To meet the challenges imposed by torrential tropical rains, the drainage layer should be as thick as possible and preferably not less than 25 mm
6	Root barrier	This layer must be present to prevent penetration of plant roots into the building fabric
7	Roof surface fall	To facilitate shedding of water from high-intensity tropical rainfall events, the fall of the finished roof should not be less than 2%
8	Thermal insulation layer	Without the thermal insulation layer, heat stored in the green roof will transmit with little hindrance to the indoor space lying below. As the Peanut green roof stores more moisture and hence more heat, it can increase the cooling load of the indoor air. It is recommended to keep the full complement of the thermal insulation layers (concrete tile, sand-cement bedding and polystyrene foam) in future green roof installations
9	Maintenance needs	The Sedum plot is difficult to maintain due to widespread decline caused by a combination of frequent or heavy summer rain and high temperature and humidity. On the other hand, the Peanut plot remained rather healthy and robust and are relatively free from growth problems. The maintenance of Peanut plot involves some simple procedures: (a) ensure that the irrigation system is in good working order all the time and can supply sufficient water without interruption; (b) remove weeds on a regular basis, at a frequency of not less than once per week in the first six months of establishment period, and thereafter not less than once per fortnight in the active growing season and not less than once per month outside the active growing season; (c) occasionally trim the stems at the edges that have spread outside the green roof area; (d) occasionally trim the stems within the plot that tend to grow upwards rather than laterally; and (e) apply maintenance dosage of slow-release fertilizers or organic fertilizers at the beginning of the active growing season
10	Irrigation water supply	To further reduce irrigation water consumption, the application rate can be reduced from 5 to 4 L/m^2/day or lower. The irrigation rate is higher than that normally adopted for ground-level planter at about 2 L/m^2/day. This is due to the more exposed and hence hotter and more windy conditions at the rooftop which can significantly raise the rate of evaporation and transpiration. Additional studies could be conducted to find the optimal water supply in different seasons and different soil depths for green roof applications. It should be stressed that the irrigation systems should be equipped with a rainfall sensor to turn off the water supply when sufficient antecedent rainwater has been received. This is an important water conservation measure
11	Ceiling moisture condition	The moisture content of the ceilings in the experimental flats was monitored from time to time throughout the study period. The results did not indicate any sign of increased moisture in the plaster and did not display any sign of water leakage. The worries of the building management that green roof installation could induce roof leaking could be accordingly allayed

[a] A research conducted at a tropical green-roof site (Jim & Tsang, 2011a, 2011b) verified that a 10 cm soil layer could notably reduce heat transmission to the underlying indoor space.

design can be modified to reduce conversion of solar energy to sensible heat that is conveyed into indoor space. The heat-sink can be suppressed by a three-pronged approach, namely replacing the rockwool with soil which has a lower thermal capacity, developing a soil-mix with less meso-pores (0.2–60 μm diameter) to trim water storage after gravitational drainage, and reducing irrigation water to an acceptable minimum to by fulfilling a proportion of the field-capacity soil-moisture constant. The research findings provide hints to enhance the quadruple passive cooling functions of green roofs, namely shading, insulation, increased albedo, and evapotranspiration to usher cooling in both upward and downward directions, and to lower indoor energy consumption.

On summer cloudy day, the heating effect is somewhat reduced. Less energy is absorbed by roof materials to suppress the cooling benefit of green roofs. Air-conditioning energy consumption has been reduced notably at Control roof. However, energy usage at the green roofs is similar to summer sunny day. As a result, the relative benefit of green roofs in comparison with Control roof has been reduced. On summer rainy day, the thermal performance of Control roof and the two green roofs tend to converge. The drastic reduction in solar input in conjunction with direct rainwater cooling have lowered outdoor air and material temperatures, and in turn curtailed downward heat flux into the indoor air. Thus the air-conditioning energy consumption of the three roofs is similarly lowered.

The field experiments involved installing two green roofs using different plant growth forms and physiology to be compared with a bare control roof on a high-rise residential building. The apartments below the three roof plots were kept vacant to permit collated indoor instrumental monitoring. The site conditions permitted a research design to monitor the holistic vertical temperature profile with precision air and surface temperature sensors. The detailed and systematic data allowed in-depth evaluation of thermal performance of the three plots with reference to outdoor air, roof surface, internal green roof materials, and indoor ceiling and air at the top apartment floor. It is possible that the green-roof thermal and energy effects could trickle downwards to the floors lying below, which could be ascertained by further empirical research. The comprehensive and high-quality data provided insights that would otherwise escape recording and attention. The findings can inform future policies and practice in green roof installation, and be applied to cities beyond Hong Kong.

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