Green Roof Research in Hong Kong: Key Findings and their Applications to Policy and Practice

Seminar Series on
New Horizon in Greening: Skyrise Greenery
Hong Kong Central Library
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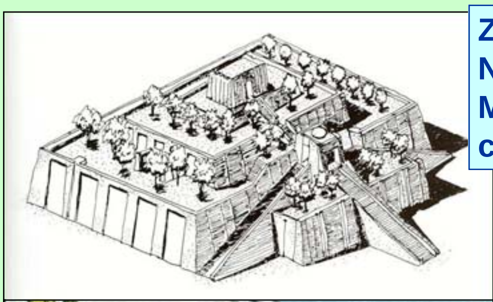
Green roof research in Hong Kong

The idea: Origin in antiquity



Ziggurat of Nanna in Ur, Mesopotamia, c. 2000 BC

Hanging Gardens of Babylon, c. 500 BC

3

The idea: Modern revival

50 great ideas for the 21st century
(The Independent, 06 August 2006)

"*21. Green roofs*

A hi-tech 21st-century version of the traditional turf roofs still found in parts of Scandinavia, a green roof is one covered with a thin layer of growing material which, in turn, supports a range of low-maintenance plants such as stonecrop and moss - all ready-grown on a kind of net matting which can be cut to fit. The results may be pretty, but it's not so much the aesthetics as the ecological and, to a lesser extent, economic benefits that really count. They're good for insects and birds, they soak up between 50 and 80 per cent of the rainwater that falls on them, and they provide natural insulation. Provided your roof is strong enough and not too steep (you can plant on slopes of up to 30 degrees), a green roof is now the perfect eco-friendly architectural accessory. (Christopher Stocks)"

Hong Kong: Compact city

Hong Kong: Barren roofs

fRese

6

Green roof and green wall sites

(1) Runme Shaw Building, rooftop, HKU (c. 400 m²)*
The first research green roof in Hong Kong
(2) Library Building, 3/F podium, HKU (c. 400 m²)
The first library in Hong Kong with a green roof accessible to users
(3) Library Building, rooftop, HKU (c. 2000 m²)*
The second research green roof in Hong Kong
(4) Electricity substation, rooftop, CLP (c. 200 m²)*
The first sky woodland in Hong Kong, composed of native tree species
(5) Railway Station, Taipo, MTRC (c. 3000 m²)*
The first railway station with green roof and vertical greening
(6) Sewage Works, Shatin, vertical greening of sewage treatment tank surfaces, DSD (c. 3500 m²)*
The first research green wall in Hong Kong
(7) Lowu Prison, rooftop of the three inmate blocks, ArchSD and CSD (c. 1200 m²)*
Believed to be the first prison in the world with green roofs
(8) Green Roof for Schools (involving thus far 10 schools with 13 sites) (total c. 4000 m²):
The first school green roof initiative in Hong Kong, successfully triggered over 50 similar projects
(a) King Ling College (Tseung Kwan O)
(b) Hong Kong and Kowloon Kaifong Women's Association Sun Fong Chung College (Taipo) (2 sites)
(c) Kau Yan College (Taipo)
(d) Caritas Tuen Mun Marden Foundation Secondary School (Tuen Mun)
(e) Tsang Mui Millennium School (Sheung Shui)
(f) Baptist Lui Ming Choi Primary School (Shatin)
(g) Tin Shui Wai Catholic Primary School (Fanling) (2 sites)
(h) Christian Alliance SW Chan Memorial College (Fanling)
(i) SKH Kei Fook Primary School (Cheung Sha Wan)
(j) Marymount Primary School (Happy Valley) (2 sites)

Total 20 sites; Total area = 14,700 m²

*** Six sites are equipped with environmental monitoring equipment**

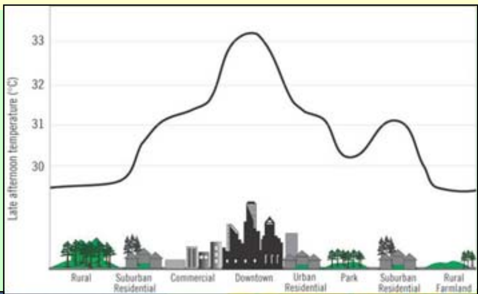
Green roof research in Hong Kong

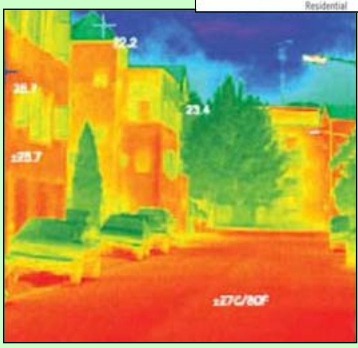
1. Introduction and Exemplaries
2. <u>HKU Runme Shaw Building</u>
3. CLP Sky Woodland
4. KCR (MTR) Taipo Railway Station
5. HKU Library Building
6. School Green Roof Project
7. DSD Vertical Greening Experiment
8. Other Green Roof and Green Wall Sites
9. Policy and Practice Implications

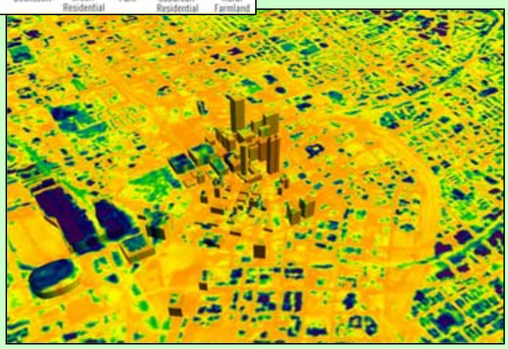
HKU: First research green roof in 2006

HKU

Green roof benefits: Suppress urban heat island effect







HKU: research on hydrological benefit

HKU: plant species trial

Oct 2007

Jan 2008

May 2008

Scientific journal research paper

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Coupling heat flux dynamics with meteorological conditions in the green roof ecosystem

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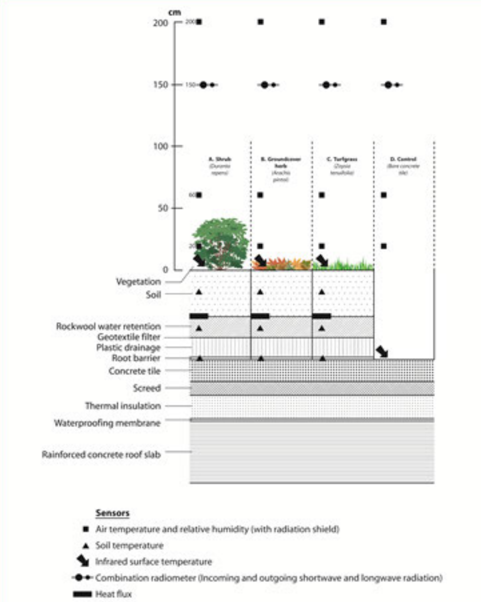
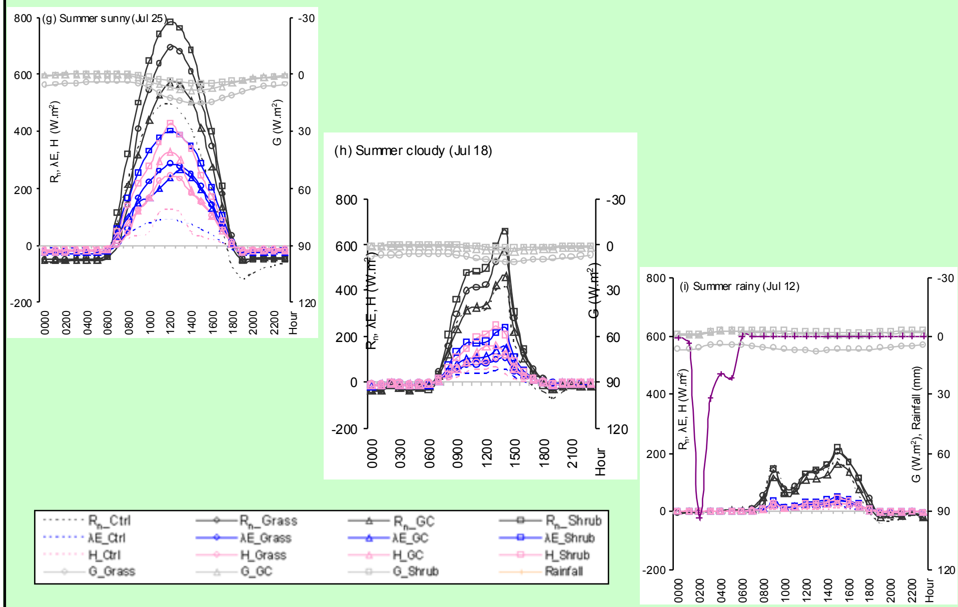
ABSTRACT

Green roofs can notably modify the thermal properties of the building envelope and adjacent air to bring environmental benefits. This study investigates the heat flux dynamics of the tropical green roof ecosystem to provide a scientific basis for design and management. Green roof experimental plots were established to monitor the total solar radiation, net radiation, and micrometeorological parameters. The data permit calculation of sensible and latent heat fluxes using the Bowen ratio energy balance (BREB) method. The results demonstrated the life cycle characteristics of heat flux components. The dynamic changes of sensible (H), latent (λE) and soil (G) heat fluxes were denoted by single-peak quadratic curves. Net radiation (R_n) was largely determined by quantity and variation trends of λE, reaching at 1300 h a maximum λE of 655 W m^{-2} and maximum H of 369 W m^{-2}. Temporal heat-flux fluctuations were strongly correlated with meteorological variables. Extreme values of H and λE correlated well with precipitation and temperature ($R^2 = 0.78$). Dynamics of heat-flux magnitude and partitioning demonstrated notable differences by daily and season periods. They displayed considerable variations in flux partitioning, with Bowen ratios strongly correlated with weather conditions and vegetation types. The energy budget of the green roof ecosystem is unbalanced with a heat loss of about 15.5% caused by soil and canopy heat reserve. The passive indoor cooling effect under the green roof is attributed to the unbalanced energy closure.

Environmental monitoring equipment



Summer cooling effect



Seasonal heat flux

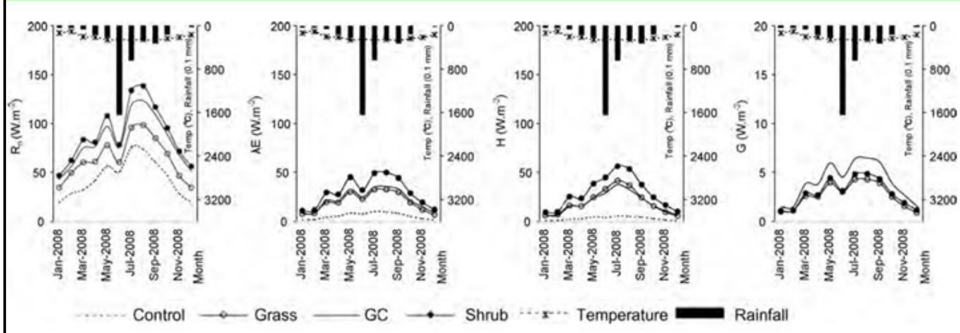


Fig. 4. Seasonal heat flux (R_n, λE, H and G) variations of four green roof experimental treatments in 2008.

Major research findings

1. The study assessed the ecological dynamics of heat flux transmission and energy balance of the green roof ecosystem so as to develop a scientific basis for its design and management.
2. The heat flux components of the green roof ecosystem express peculiar life cycle characteristics. The dynamic changes of fluxes in sensible heat, latent heat and soil heat demonstrate single-peak quadratic curves.
3. The net radiation determines the quantity and variation trends of latent heat flux. Diurnal and seasonal variations of heat fluxes form hyperbola curves.
4. Seasonal heat fluxes vary with the fluctuation of meteorological driving forces. Extreme values of sensible heat and latent heat fluxes correlate well with rainfall and temperature.
5. The dynamics of heat flux magnitude and partitioning demonstrate notable differences amongst daily time periods and seasons which are dependent on group characteristics.

Major research findings

6. Temporal heat-flux fluctuations are strongly correlated with meteorological variables. Latent heat and sensible heat fluxes show major differences in response to precipitation. Temperature is one of the key contributors to heat flux. Latent heat flux is inversely related to atmospheric pressure.
7. Evaporation is the principal determinant of latent heat flux and soil moisture. There is a considerable range in flux partitioning characteristics (Rn, λE, H, and β).
8. Fluctuation trends of Bowen ratio are strongly influenced by weather condition and vegetation type.
9. The cooling effect of the green roof ecosystem is due to the imbalance of energy closure. The characteristics of plant canopy and soil properties contribute to heat loss of green roof ecosystem which leads to an unbalanced energy closure. Meteorological conditions, such as the amount, duration and density of clouds and precipitation incur variations in heat flux components in relation to the energy closure analysis.

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Simulation of thermodynamic transmission in green roof ecosystem

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Multi-layer shield

ABSTRACT

Green roofs entail the creation of vegetated space on the top of artificial structures. They can modify the thermal properties of buildings to bring cooling energy conservation and improve human comfort. This study evaluates the thermodynamic transmission in the green roof ecosystem under different vegetation treatments. Our model simulation is based on the traditional Bowen ratio energy balance model (BREBM) and a proposed solar radiation shield effectiveness model (SEM). The BREBM investigates energy absorption of different components of radiation, and the SEM evaluates the radiation shield effects. The proposed model is tested and validated to be efficient to simulate solar energy transmission in green roofs, with some major findings. Firstly, the solar radiation transmission processes might be considered as free vibration motion. Daytime positive heat storage of the green roof is 350–520 W m^{-2} on an hourly basis. Nighttime or afternoon negative value registers a rather constant magnitude of −60 W m^{-2}. Daily net average is positive around 155–210 W m^{-2}. Secondly, solar radiation vibration is highly correlated with plant structure. The canopy reflectance and transmittance are strongly correlated (R^2 = 0.87). The multi-layer shrub treatment has the highest shield effectiveness (0.34), followed by two-layer groundcover (0.27), and single-layer grass (0.16). Green roof vegetation absorbs and stores large amounts of heat to form an effective thermal buffer against daily temperature fluctuation. Vegetated roofs drastically depress air temperature in comparison with bare ground (control treatment). Finally, the thermodynamic model is relatively simple and efficient for investigating thermodynamic transmission in green roof ecosystem, and it could be developed into a broad solar radiant land cover model.

Parameters in radiation shield effectiveness of vegetation

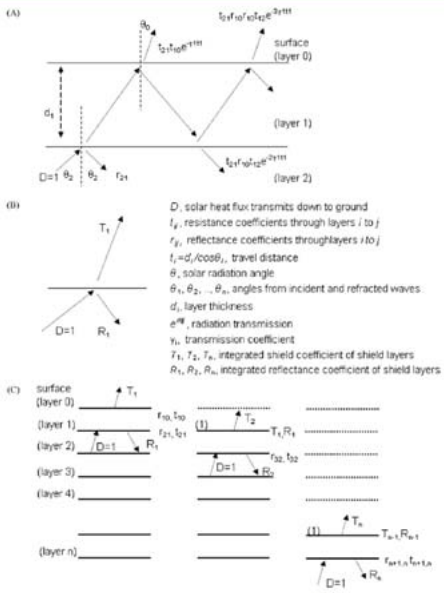

Fig. 1. The parameters involved in the radiation shield effectiveness of green roof vegetation. A: process of single-layer radiation transmission; B: computational model of single-layer shielding; C: computational model of multi-layer shielding.

Observed heat flux daily cycles

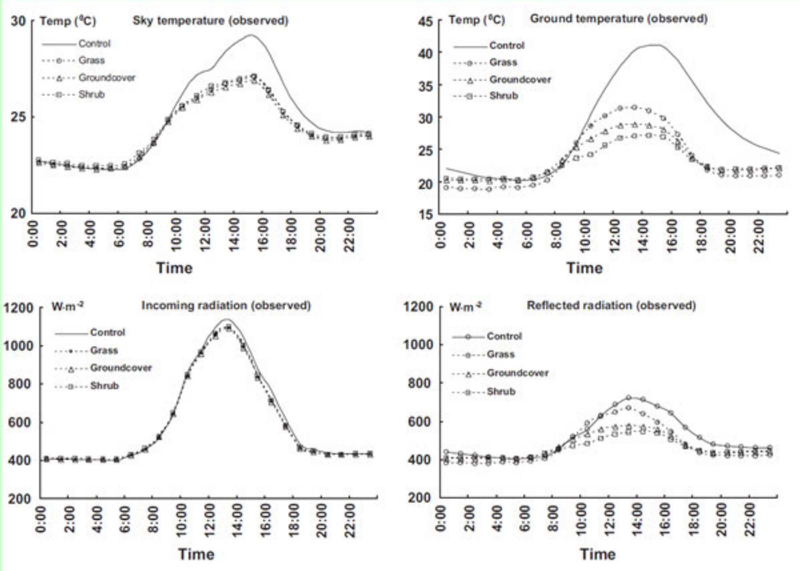

Fig. 3. Observed heat flux daily cycles of the experimental green roof plots in 2008.

Shield effective model for three vegetation types

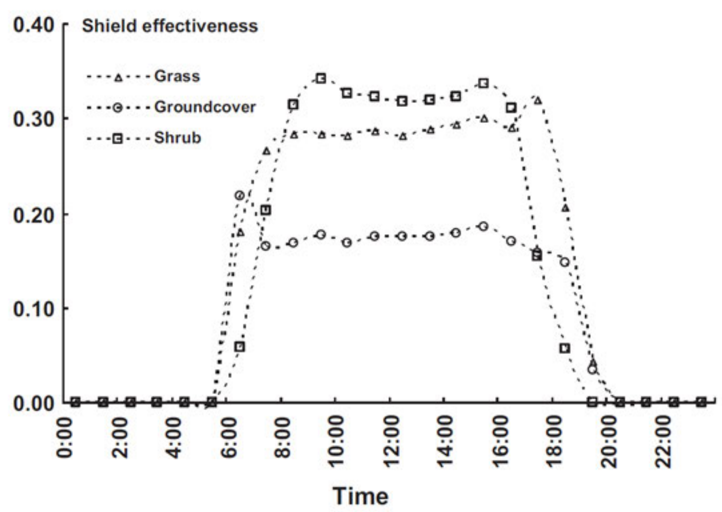

Fig. 7. Vegetation shield effectiveness for three vegetation types in the green roof ecosystem for 2008.

Major research findings

1. We adopted an ecological approach by evaluating both the abiotic and biotic components of the green roof as a living system. We devised a field experiment to monitor the total solar radiation and net radiation, and to obtain detailed microclimatic data to calculate the sensible and latent heat fluxes of the green roof ecosystem with the traditional Bowen ratio energy balance method. We also evaluated green roof insulation effects on basis of the proposed solar radiation shield effectiveness model.
2. The dynamics of heat flux magnitude and partitioning demonstrate notable differences amongst daily time periods which are dependent on treatment characteristics. Ambient temperature is one of the key contributors to heat flux. Evaporation is the principal determinant of latent heat flux and soil moisture. The characteristics of plant canopy and soil properties contribute to the differential heat loss of the green roof ecosystem which leads to an unbalanced energy closure.
3. Radiation transmission and shield effects strongly correlate with vegetation structure and canopy transmittance and reflectance. A key function of the vegetation layer is to create a quiescent layer of air immediately above the roof surface.
4. Green roof vegetation has the capacity to absorb and store large amounts of heat to buffer against daily temperature fluctuations. The more complex vegetation structures have higher values of reflectance and transmittance, and absorb more radiant energy.
5. Predictions of thermal energy management benefits are possible only with the assistance of building envelope analysis techniques that can integrate all of these effects. As a result, the potential benefits of green roofs in managing energy can be approximated in different areas under different circumstances.

Scientific journal research paper

Effect of vegetation biomass structure on thermal performance of tropical green roof

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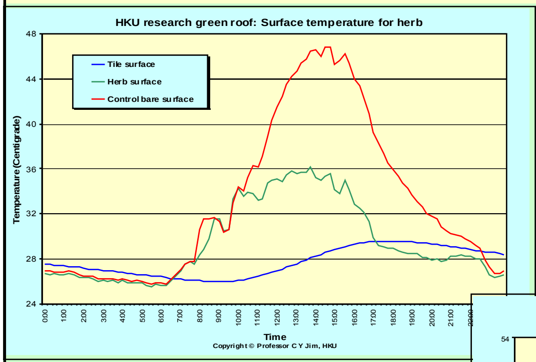
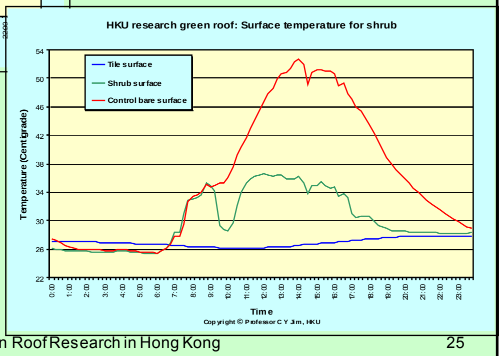
Landscape and Ecological Engineering (in press)

Diurnal cooling benefit of two vegetation types





Material temperatures in three layers

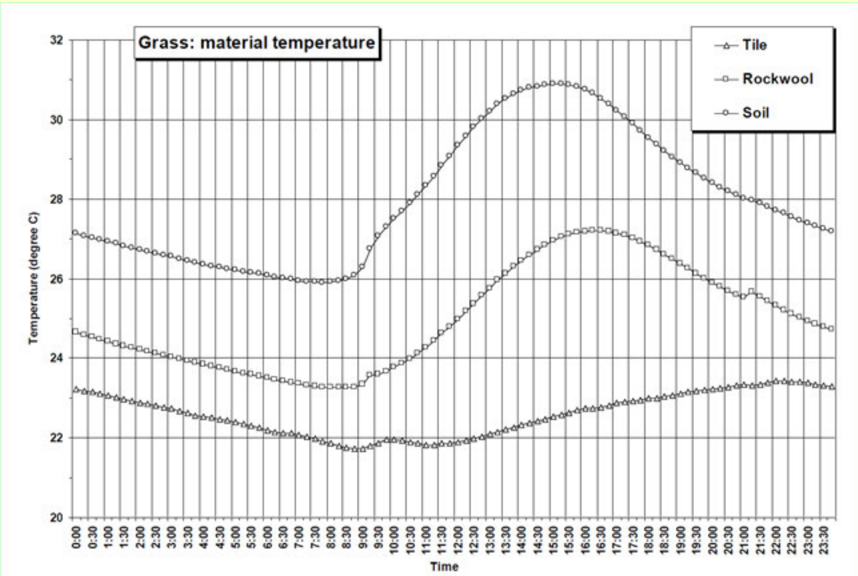


Fig. 10. Material temperature in the soil, rockwool and tile layers at the grass green roof site.

Material temperatures in three layers

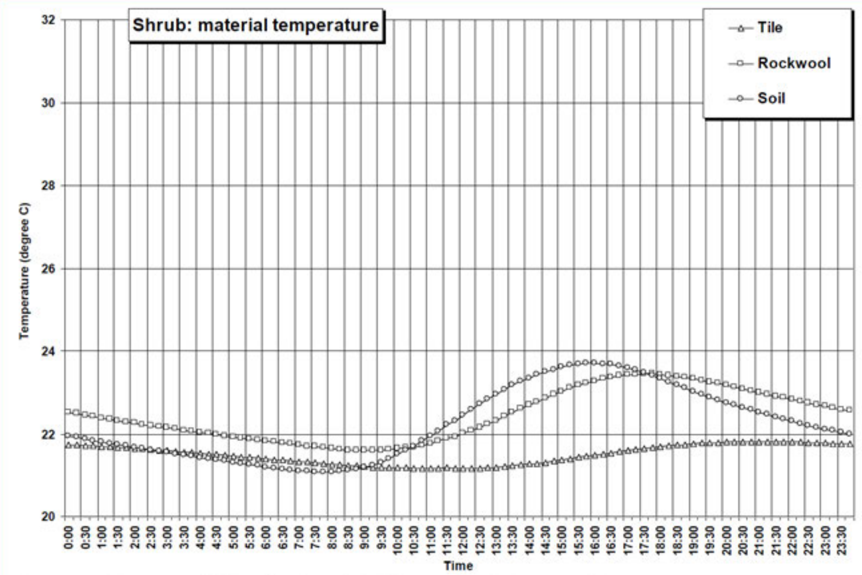


Fig. 12. Material temperature in the soil, rockwool and tile layers at the shrub green roof sites.

Major research findings

1. Differential effects of three vegetation types of different biomass structure on green roof cooling impacts
2. Suppression of daily maximum and minimum temperature, but not of diurnal temperature range
3. Nighttime cooling effect of vegetated roof not better than control (bare) roof
4. Grass roof cools air temperature better than groundcover and shrub roofs
5. In daytime, grass develops a miniature suspended temperature inversion (STI) and shrub develops a canopy temperature inversion (CTI)
6. Shrub has the densest and most complex biomass structure but creates the most extreme diurnal air temperature regime
7. Grass has the simplest biomass structure, but it is more able to bring passive air cooling

Major research findings

8. Groundcover and shrub with a concentration of transpirational foliage elevated above the soil, create passive cooling respectively by perched thermal discontinuity (PTD)
9. The air gap of the plastic drainage layer arrested downward heat transmission in all vegetated plots to form a subsurface thermal discontinuity (STD)
10. Little heat moves from soil and rockwool layers to the tile, indicating the effective insulation provided by the drainage layer
11. The natural passive cooling effect of green roofs could play a useful role in ameliorating the urban heat stresses, and providing the collateral ecological and amenity benefits
12. Both daytime and nocturnal urban heat island effect could be ameliorated by irrigated green roofs
13. The findings provide an alternative dimension to the choice of vegetation and system design for roof greening in tropical cities, as a part of the bioclimatic building design making use of natural and sustainable cooling features

Scientific journal research paper

Modeling the heat diffusion process in the abiotic layers of green roofs

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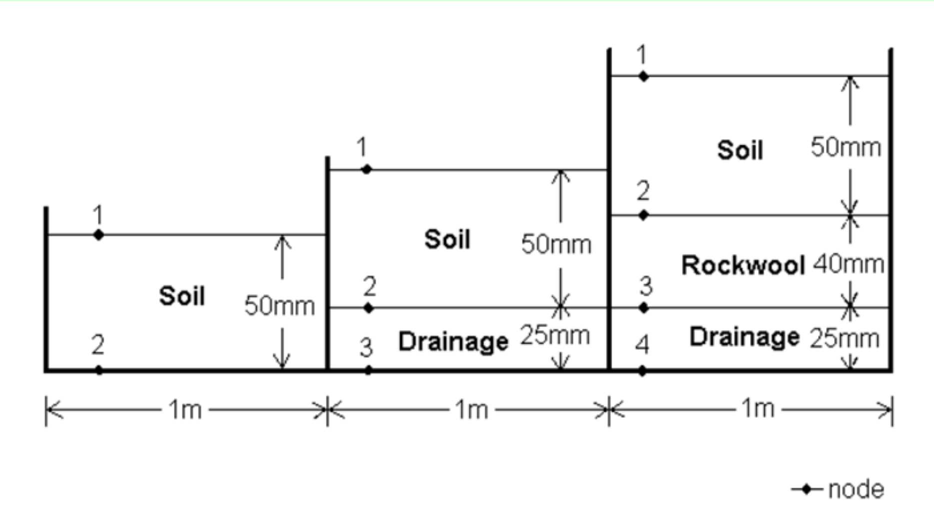
Energy and Buildings (in press)

Experimental design



Modelled and measured temperature: rainy day

Modelled and measured temperature: after rainy day

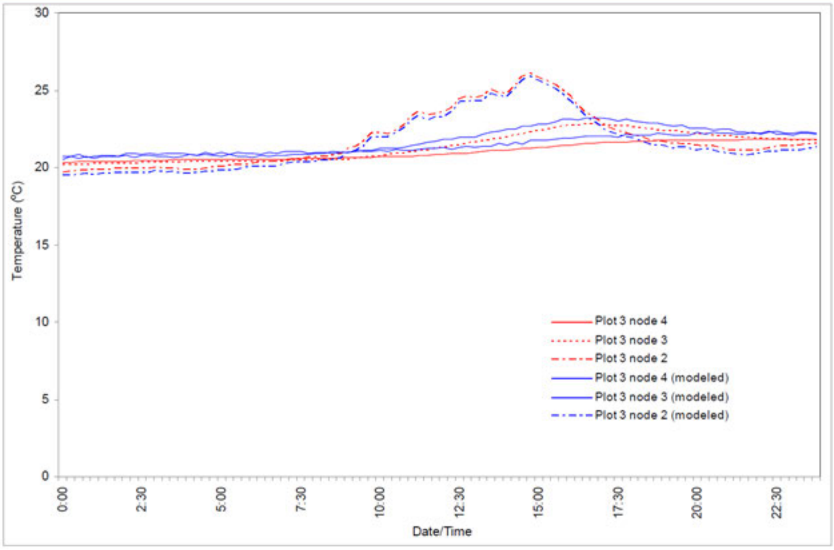


Fig. 9. Comparison of daily modeled and measured temperatures at nodes 2-4 of Plot 3 on a sunny day after a rainy day (28 March 2008).

Temperature variations at plot bottom

Major research findings

1. A theoretical model has been developed successfully to evaluate the heat diffusion process of the soil, rockwool and plastic drainage materials used in green roof installation
2. The lowest temperatures and the narrowest temperature ranges occur in the complex Plot 3, because the rockwool can retain an appreciable amount of rainwater for evaporative cooling through the soil surface on the sunny day after a rainy day, and to raise the specific heat capacity of the water-rockwool-air mixture
3. The plastic drainage sheet with ample internal air spaces has been found to be a highly effective thermal insulation layer
4. The seasonal and weather effects do not significantly affect the accuracy of the theoretical model
5. The findings contradict with researches in the temperate region that the thermal dissipation in the vegetated roof with dense vegetation is lower than the thermal insulated bare roof
6. Overall, the abiotic components of the modern green roof contribute significantly to the thermal performance and cooling effect of the elevated green spaces.

Scientific journal research paper

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Game-theory approach for resident coalitions to allocate green-roof benefits

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Abstract. Roof greening in cities provides a range of environmental, economic, and social benefits. However, the lack of motivation among property owners in high-rise buildings poses an intractable obstacle to its wide implementation in compact cities. Cooperation amongst stakeholders, from individual-building to city-block scales, could facilitate adoption of green roofing, with implications for urban sustainability. This study is an attempt to evaluate the net gain from roof greening in terms of apportioned collective costs and benefits to a group of property owners. With government tax exemption to encourage green-roof installation, a fair-allocation scheme, based on the Shapley value, is adopted to distribute the net gain in a partnership structure. A case study in Hong Kong serves to illustrate the application of the method to allocate theoretically the sharable gain of roof greening translated into monetary terms. The results verify the importance of individual owners in different coalition configurations in moulding the benefit profile. The crux of the financial incentive scheme is the enhanced rewards to optimized cooperation, and the pump-priming triggering of cooperation and action. The benefits of green roofs could be maximized by their widespread and contiguous, rather than piecemeal, installation. Green roofs could reduce both capital and recurrent public expenditures in stormwater management, healthcare, and green-space provision, the savings from which would be more than enough to fund the tax-exemption scheme. The findings yield convincing justifications for government financial incentives to promote public–private partnerships and cooperative coalitions of stakeholders in roof greening in compact urban areas.

Environment and Planning A (in press)

Cost-benefits of green roof in HK context

1. Stormwater management
2. Health care service
3. Green space provision
4. Costs of constructing and maintaining green roofs
5. Reduction in energy consumption
6. Urban sustainable development

Computed costs and benefits

Table 1. Building information, and costs and benefits before and after green roof installation

									Shapley values							
Building information					Cost				Small coalition size			Large coalition size				
Building no.	Floor	Roof area (m^2)	(%)	Total floor area (m^2)	Before installation (HK$)	(%)	After installation (HK$)	(%)	Period	Scheme 1	(%)	Scheme 1	(%)	Scheme 2	(%)
1	19	165	1.90	3141	1216835	1.93	51529	1.90	T2	615502	2.14	548233	1.91	551682	1.92
2	17	387	4.46	6586	2561668	4.07	120772	4.46	T4	1118539	3.89	1170436	4.07	1220434	4.25
3	13	317	3.65	4124	1622337	2.58	98903	3.65	T2	680217	2.37	730618	2.54	880572	3.06
4	25	73	0.84	1833	704501	1.12	22854	0.84	T1	211043	0.73	317036	1.10	285885	0.99
5	6	136	1.57	817	339050	0.54	42432	1.57	T1	153235	0.53	147104	0.51	288547	1.00
6	12	153	1.76	1835	724793	1.15	47679	1.76	T1	239281	0.83	322788	1.12	410181	1.43
7	21	181	2.08	3801	1468285	2.33	56433	2.08	T2	648315	2.26	663130	2.31	638095	2.22
8	18	327	3.76	5889	2286053	3.63	101999	3.76	T4	1095970	3.81	1039457	3.62	1061369	3.69
9	15	274	3.15	4106	1604791	2.55	85329	3.15	T2	666788	2.32	720102	2.50	810998	2.82
10	21	306	3.52	6424	2481371	3.94	95371	3.52	T4	1131896	3.94	1130278	3.93	1078368	3.75
11	8	319	3.66	2548	1032248	1.64	99312	3.66	T1	374912	1.30	456494	1.59	735012	2.56
12	24	575	6.61	13796	5308770	8.44	179207	6.61	T7	2071228	7.20	2465528	8.58	2187846	7.61
13	26	402	4.62	10440	4009204	6.37	125181	4.62	T7	1469947	5.11	1845906	6.42	1603489	5.58
14	14	310	3.56	4340	1701303	2.70	96637	3.56	T3	811866	2.82	768034	2.67	889429	3.09
15	16	209	2.40	3340	1302200	2.07	65081	2.40	T2	639126	2.22	587284	2.04	638106	2.22
16	23	312	3.59	7179	2765816	4.40	97313	3.59	T5	1264683	4.40	1262106	4.39	1158806	4.03
17	24	705	8.11	16920	6510918	10.35	219788	8.11	T7	3849095	13.39	3070369	10.68	2683274	9.33
18	23	344	3.96	7913	3048290	4.84	107252	3.96	T6	1460930	5.08	1394855	4.85	1277156	4.44
19	21	326	3.75	6850	2645785	4.21	101690	3.75	T5	1240301	4.31	1207081	4.20	1149819	4.00
20	23	354	4.07	8139	3135389	4.98	110316	4.07	T6	1470930	5.12	1435162	4.99	1313648	4.57
21	6	450	5.18	2701	1121248	1.78	140326	5.18	T1	574203	2.00	487057	1.69	954234	3.32
22	18	326	3.75	5865	2276620	3.62	101578	3.75	T3	960639	3.34	1035395	3.60	1056989	3.68
23	15	358	4.12	5373	2100106	3.34	111666	4.12	T3	921132	3.20	953439	3.32	1061310	3.69
24	22	317	3.65	6979	2691968	4.28	98897	3.65	T5	1250791	4.35	1227642	4.27	1147950	3.99
25	5	209	2.41	1047	443073	0.70	65268	2.41	T1	211911	0.74	191072	0.66	424223	1.48
26	26	177	2.04	4605	1768367	2.81	55214	2.04	T3	864466	3.01	801852	2.79	707262	2.46
27	23	377	4.33	8666	3338649	5.31	117468	4.33	T6	1494268	5.20	1534009	5.34	1398809	4.87
28	23	306	3.52	7031	2708754	4.31	95306	3.52	T5	1257180	4.37	1235927	4.30	1134899	3.95
Total		8695	100.00		62918393	100.00	2710803	100.00		28748393	100.00	28748393	100.00	28748393	100.00

Net gains of roof greening

Table 2. Example of calculations of net gains in the core of T_3 (buildings # 14,26,23,22) (at US$1=HK$7.8)

Members	Total floor area (m^2)	Tax exemption rate (%)	Cost before installation (HK$)	Cost after installation (HK$)	Characteristic value (HK$)	
{14}	309.98	0.1	1701302.73	96636.70	1701302.73x0.1-96636.7 =	73493.57
{26}	177.11	0.1	1768367.22	55214.29	1768367.22x0.1-55214.29 =	121622.43
{23}	358.19	0.1	2100105.93	111666.23	2100105.93x0.1-111666.23 =	98344.36
{22}	325.83	0.1	2276620.37	101577.96	2276620.37x0.1-101577.96 =	126084.08
{22,23}	684.02	0.2	4376726.30	213244.19	4376726.3x0.2-213244.19 =	662101.07
{22,26}	502.94	0.2	4044987.59	156792.25	4044987.59x0.2-156792.25 =	652205.27
{23,26}	535.30	0.2	3868473.15	166880.52	3868473.15x0.2-166880.52 =	606814.11
{22,23,26}	861.13	0.2	6145093.52	268458.48	6145093.52x0.2-268458.48 =	960560.22
{14,22}	635.81	0.2	3977923.10	198214.66	3977923.1x0.2-198214.66 =	597369.96
{14,23}	668.17	0.2	3801408.66	208302.93	3801408.66x0.2-208302.93 =	551978.80
{14,22,23}	994.00	0.2	6078029.03	309880.89	6078029.03x0.2-309880.89 =	905724.92
{14,26}	487.09	0.1	3469669.95	151850.99	3469669.95x0.1-151850.99 =	195116.01
{14,22,26}	812.92	0.2	5746290.32	253428.95	5746290.32x0.2-253428.95 =	895829.11
{14,23,26}	845.28	0.2	5569775.88	263517.22	5569775.88x0.2-263517.22 =	850437.96
{14,22,23,26}	1171.11	0.5	7846396.25	365095.18	7846396.25x0.5-365095.18 =	3558102.95

Major research findings

1. Applicability of Shapley value (game theory) approach in forming coalitions and allocating benefits
2. Tax exemption can mobilize interest and promote roof greening
3. Stakeholders, including building owners and the government, can benefits from coalition formation
4. Importance of every owner in the cooperation regime
5. Benefits can be maximized by widespread rather than piecemeal installation
6. Ample justifications for government to encourage installation by offering attractive financial incentives
7. More benefits in high-density neighbourhoods
8. Both the administration and residents can share the benefits of roof greening in a long-term, community-wide and public-private-partnership win-win scenario

Green roof research in Hong Kong

Scientific book chapter

Scientific journal research paper

Ecological design of rooftop native woodland for sustainable cities

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Abstract

The green roof idea is rooted in antiquity, with a modern revival about 50 years ago. Most green roofs are extensive with a simple herbaceous cover. The intensive type with trees and shrubs is often dominated by horticultural design requiring significant maintenance inputs. Green roofs could adopt an innovative ecological or naturalistic design to establish native woodlands to bestow high-level ecological benefits and environmental amelioration such as cooling and suppression of urban heat island effect. Hong Kong's excessively compact urban development mode leaves meagre ground-level green spaces. Green roofs offer alternative greening sites to reduce the environmental stresses associated with urbanization. A low-rise electricity substation has been earmarked for roof greening, and the rooftop urban woodland idea was implemented. Ecodesign principles were applied to establish a humid-subtropical native woodland that can attract local wildlife and usher valuable ecosystem services in a densely developed residential area.

Keywords: ecological design, intensive green roof, urban woodland, urban biodiversity, ecosystem services.

International EcoBalance 2010 Conference
Tokyo, 9-12 November 2010

Sky woodland: The vision

CLP

Emulation of subtropical native woodland

- Emulates the natural woodland in terms of high vegetation coverage, high biomass volume, high leaf area index, high species-area index, and complex biomass structure

Camellia hongkongensis Hong Kong Camellia

Soil depth and rooting room

- Provides sufficient soil depth of 1 m to permit the healthy spread of tree roots, based on tree root research

Woodland establishment

Habitat island and stepping stone

Major implications and applications

- Successful application of ecological concepts and ecological engineering to establish the most complex green roof in HK
- Feasible to use native trees to create a sky woodland on rooftop
- Diversified species composition and biomass structure
- Enhance urban wildlife (birds, butterflies, etc.)
- Cost-effective green roof installation
- Significant cooling effect by evaporation and transpiration
- Significant insulation effect by vegetation and soil layers
- Lower indoor temperature and reduce electricity consumption
- Reduce of stormwater drainage
- Improve quality of stormwater and reduce water pollution
- Notable landscape and amenity values for neighbourhood
- Exemplary demonstration project for HK and the region
- Findings for technology sharing and transfer

Scientific journal research paper

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Biophysical properties and thermal performance of an intensive green roof

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ABSTRACT

Green roofs have been increasingly enlisted to alleviate urban environmental problems associated with urban heat island effect and stormwater quantity and quality. Most studies focus on extensive green roofs, with inadequate assessment of the complex intensive type, subtropical region, and thermal insulation effect. This study examines the physical properties, biological processes, and thermal insulation performance of an intensive green roof through four seasons. An experimental woodland installed on a Hong Kong building rooftop was equipped with environmental sensors to monitor microclimatic and soil parameters. The excellent thermal performance of the intensive green roof is verified. Even though our site has a 100 cm thick soil to support tree growth, we found that a thin soil layer of 10 cm is sufficient to reduce heat penetration into building. Seasonal weather variations notably control transpiration and associated cooling effect. The tree canopy reduces solar radiation reaching the soil surface, but the trapped air increases air temperature near the soil surface. The substrate operates an effective heat sink to dampen temperature fluctuations. In winter, the subtropical green roof triggers notable heat loss from the substrate into the ambient air, and draws heat upwards from warmer indoor air to increase energy consumption to warm indoor air. This finding deviates from temperate latitude studies. The results offer hints to optimize the design and thermal performance of intensive green roofs.

Environmental monitoring

➢Equipped with environmental monitoring equipment to glean data for scientific assessment of the benefits under humid-subtropical and densely-urbanized conditions

Air temperature in summer and winter

Canopy and ground temperature in summer and winter

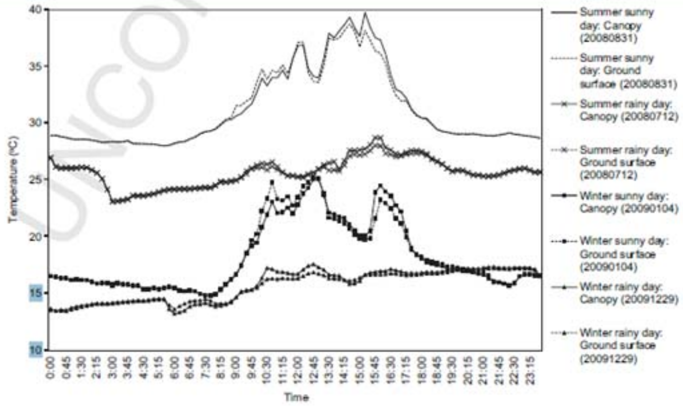


Fig. 2. Diurnal woodland canopy and ground-surface temperature in summer and winter on sample days of sunny and rainy weather conditions in 2008 and 2009.

Soil temperature in summer and winter

Soil moisture on sunny summer day

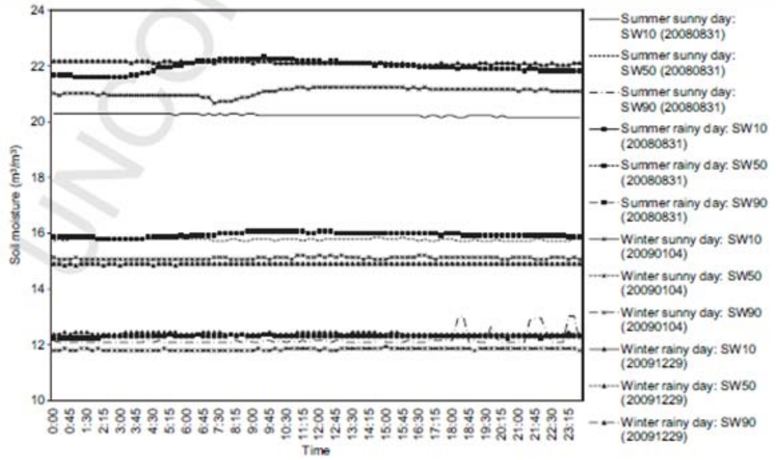


Fig. 5. Diurnal soil moisture changes at three depths in summer and winter on sample days of sunny and rainy weather conditions in 2008 and 200

Heat flux in the sky woodland under different weather conditions

Major research findings

1. The seasonal effect is significant for air temperature at different heights, soil surface temperature, soil moisture, tree canopy and ground surface temperature; it is not significant for soil temperature at different depths, tile and concrete slab temperature.
2. The weather effect is significant for diurnal air temperature at different heights, canopy, ground surface, and soil surface temperature; it is not significant for diurnal soil temperature and moisture at different depths (except on the soil surface), tile and concrete slab temperature.
3. The cooling effect due to transpiration rate (latent heat absorption) varies widely depending on seasonal and weather conditions, and it peaks in early autumn due to rather warm but dry weather condition.
4. The tree canopy layer could reduce solar radiation reaching the soil surface by reflecting some incident solar radiation back to the atmosphere; the air trapped in the canopy could reduce the convective heat loss and increase the air temperature near the soil surface.
5. The soil substrate layer operates as a large heat sink to reduce temperature fluctuation. The soil absorbs solar radiation on sunny daytime and retains it as storage heat. In nighttime, the storage heat is dissipated as sensible and convective heat.

Major research findings

6. On rainy days, soil absorbs rain water to increase the soil heat capacity to store a considerable amount of energy without increasing the soil temperature to achieve good thermal insulation performance.
7. The experiment demonstrates that soil thermal insulation performance does not require a thick soil. A thin soil layer of about 10 cm is sufficient to reduce substantially heat penetration into the building.
8. In winter, heat flows notably upwards from the substrate to the ambient air. The warmer indoor air below the roof slab creates a temperature gradient to draw heat upwards into the substrate and hence to dissipate in the air as sensible and latent heat. The resulting cooling of the building interior creates demands for more energy consumption to warm the indoor air. This finding contradicts the temperate latitude studies that point to reduction in heat loss through the roof in winter to lower heating energy consumption.

Green roof research in Hong Kong

1. Introduction and Exemplaries
2. HKU Runme Shaw Building
3. CLP Sky Woodland
4. KCR (MTR) Taipo Railway Station
5. HKU Library Building
6. School Green Roof Project
7. DSD Vertical Greening Experiment
8. Other Green Roof and Green Wall Sites
9. Policy and Practice Implications

Railway station: Green roof

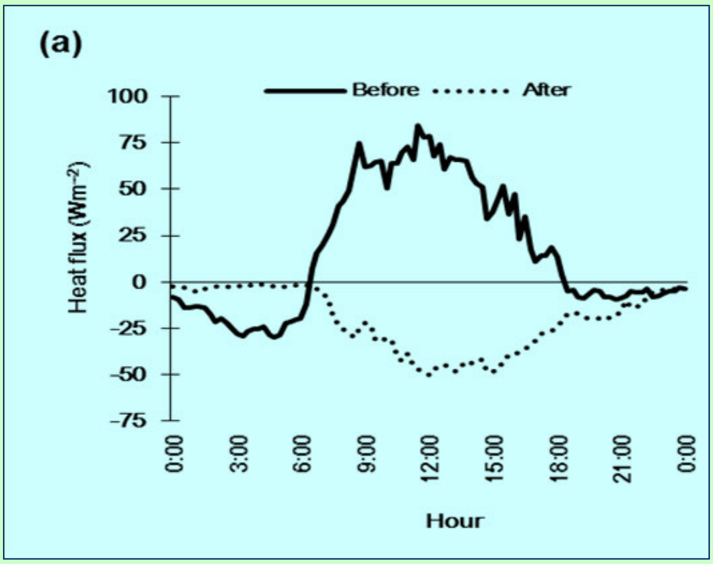
Taipo Railway Station

Railway station: Green wall

Taipo Railway Station

Temperature on typical summer sunny day

Heat flux on typical summer sunny day



Major research findings

1. The monthly analyses show great variations in diurnal thermal performance of the green roof. On average, the extensive green roof could reduce daily maximum temperature at the concrete roof surface at Tr by 1.5-4.6°C and at U10 by 0.8-1.4°C. The effect of green roof on air temperature at 160 cm is marginal. The surface temperature on the green roof surface at Ts is even higher than Tr on bare roof by 4.2-7°C due to limited solar protection by plants.
2. Solar radiation and relative humidity are the key meteorological factors with a bearing on the green roof thermal effect. High solar radiation combined with low relative humidity could optimize the thermal performance of the green roof.
3. Soil moisture enhances the green roof cooling effect by storing heat, dampening diurnal temperature fluctuations, and sustaining evapotranspiration and associated cooling.
4. Rainfall can offset the relative temperature reduction of the green roof due to rapid cooling of the bare roof.
5. Wind can reduce surface and air temperature of the green roof by enhanced evapotranspiration, but it has no significant correlation with temperature reduction because it could effectively and simultaneously dissipate the stored heat of the bare roof.

Major research findings

6. The thermal effect of the green roof displays considerable variations under different weather conditions. It is optimal on the sunny summer day, declines on the cloudy day, and tends to be negligible on the rainy day.
7. The reduction in maximum temperature by the green roof at Tra, Ts, U10 and U160 can reach respectively 11°C, 3.2°C, 4.5°C and 3.4°C on the sunny summer day. The values decline to 7.2°C and 2.3°C at Tra and U10 on cloudy days, which are associated with no significant reduction at U160 and even an increase at Ts. The green roof serves the role of thermal conservation on the rainy day with minor temperature reduction except for a slight nocturnal cooling.
8. The green roof could reduce cooling load by 0.9 kWh m^{-2} on the sunny day and 0.57 kWh m^{-2} on the cloudy day, but it can add a slight cooling load to the building on the rainy day. Overall, the 484 m^2 green roof has a potential for energy saving for indoor summer air-conditioning that is equivalent to 6.3×10^4 kWh.
9. Especially on fine sunny days and to a lesser extent on cloudy days, the solar energy heats up the bare roof considerably to contribute to heat flux into the building indoor space, which in turn demands fossil fuel energy to cool down the indoor air by air-conditioners. The same solar energy works in the opposite direction on the green roof to propel evapotranspiration and to cool down the roof mainly during daytime. The green roof has transformed the consumptive and unwelcomed use of solar energy into productive and beneficial use.

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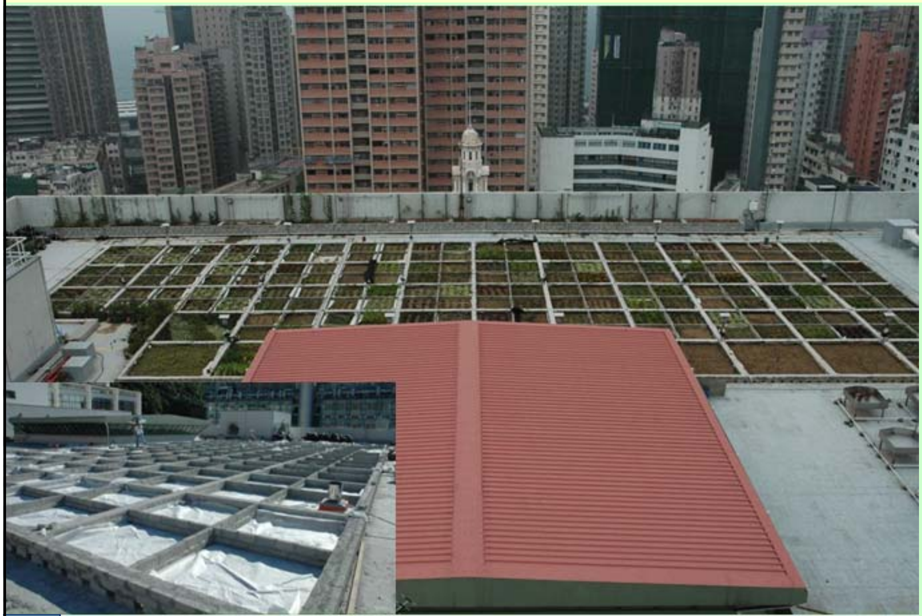
HKU: Second research green roof



HKU | CY Jim: Green Roof Research in Hong Kong | 67

HKU: Second research green roof

Ipomoea cairica | CY Jim: Green Roof Research in Hong Kong | *Thunbergia grandiflora*

HKU: Second research green roof

Hydrological research

Green roof research in Hong Kong

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School green roof project

- Proposal submitted to Hongkong Bank Foundation in July 2007
- Funding approval in October 2007
- Donate green roofs to 10 schools
- Each school to receive about 400 m^2 of lawn plus irrigation system
- Maintenance shouldered by school

Completed school green roof

Sun Fong Chung College

School green roof project

TSW Catholic Primary Sch

School green roof project

Tsang Mui Millennium Sch

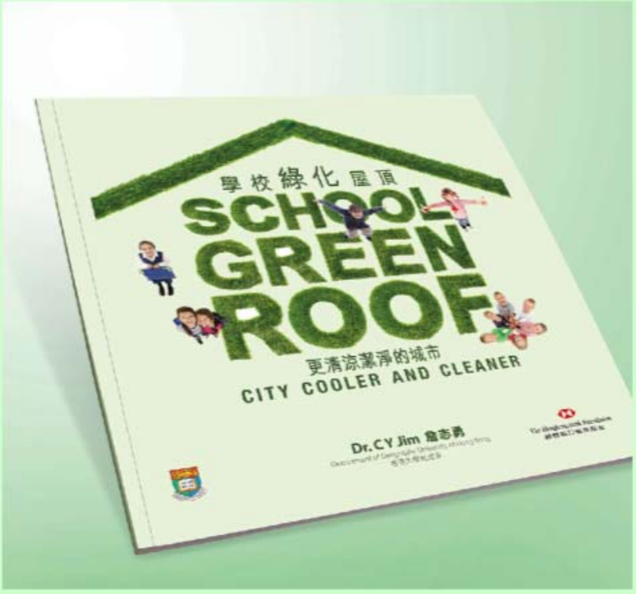
Recreational activities

Innovation dissemination: School

	2008-2009		
16	San Wui Commercial Society Secondary School	Extensive Green Roof	$486,500
17	Buddhist Wong Wan Tin College	天空之城: 空中花園計劃	$185,600
18	Cognitio College (Hong Kong)	Stop Global Warming: Green Roof	$403,800
19	Gigamind English Primary School	Extensive Green Roof	$302,200
20	H.K.T.A. Tang Hin Memorial Secondary School	Eco-Greenroof System	$460,400
21	TWGHs Yau Tze Tin Memorial College	Butterfly Garden on the Roof	$338,000
22	Hong Chi Pinehill No.2 School	Eco Green Roof	$264,688
23	Maryknoll Fathers' School (Primary Section)	Green Roof Green School	$379,875
24	Chuk Lam Ming Tong Care & Attention Home For The Aged	Vitality of Greenroof in Chuk Lam	$45,350
25	Ping Shek Estate Catholic Primary School	Children under the Green Roof	$734,250
26	Lee Kau Yan Memorial School	Green Roof	$416,000
27	Holy Family Canossian School (Kowloon Tong)	Green Roof System	$423,000
28	Shatin Methodist Primary School	Organic Sky Garden with Renewable Energy	$426,420
29	HKCWC Fung Yiu King Memorial Secondary School	Green Roof Action	$317,450
30	Christian Alliance SY Yeh Memorial Primary School	Yeh's Roof-top Garden Cum Environment Learning	$346,500
31	Caritas Lok Kan School	Project E.R. II (Environmental Roof)	$810,370
		Subtotal	**$12,498,303**
		Grand total	**$16,488,973**

ECF funding for schools

Educational use of school green roof



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DSD sewage treatment works: Vertical greening

CY Jim: Green Roof Research in Hong Kong

Shatin DSD Sewage Plant

DSD sewage treatment works: Vertical greening

Wisteria sinensis

CY Jim: Green Roof Research in Hong Kong

Lonicera japonica

Green roof research in Hong Kong

Lo Wu new prison: Green roof

Lowu CSD

Lo Wu new prison: Green roof

Lowu CSD

HKU: Vertical greening project

HKU

HKU: Vertical greening project

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Green roof research in Hong Kong

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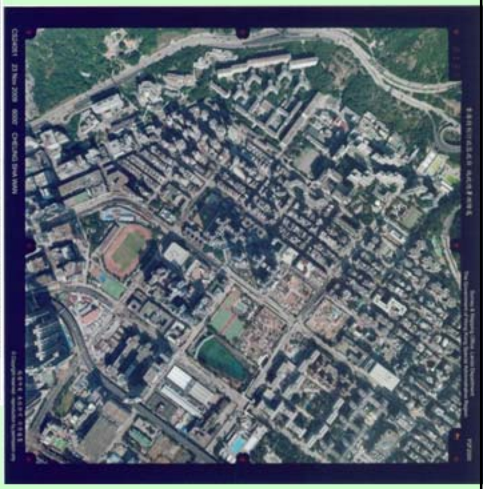
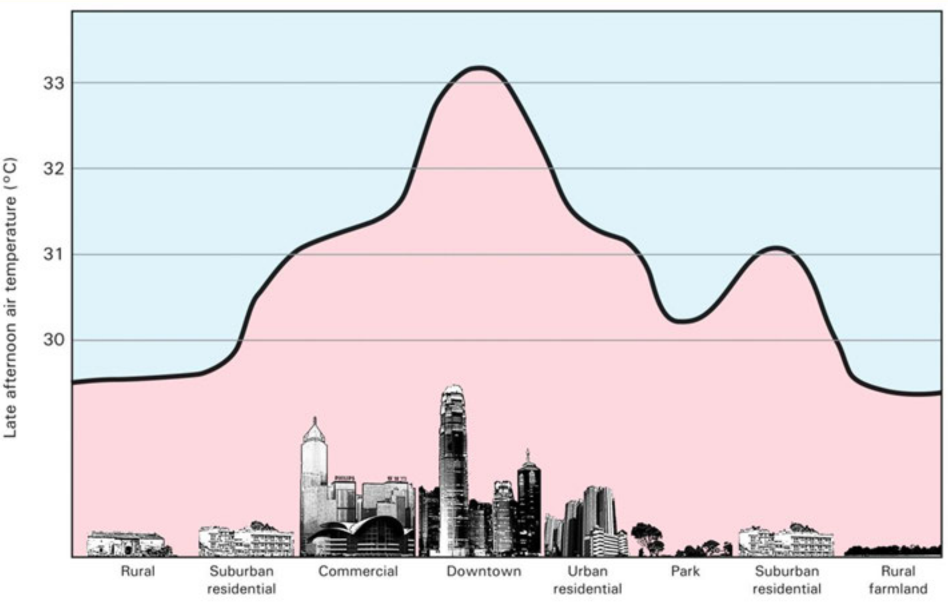
High built-up density and heat absorption

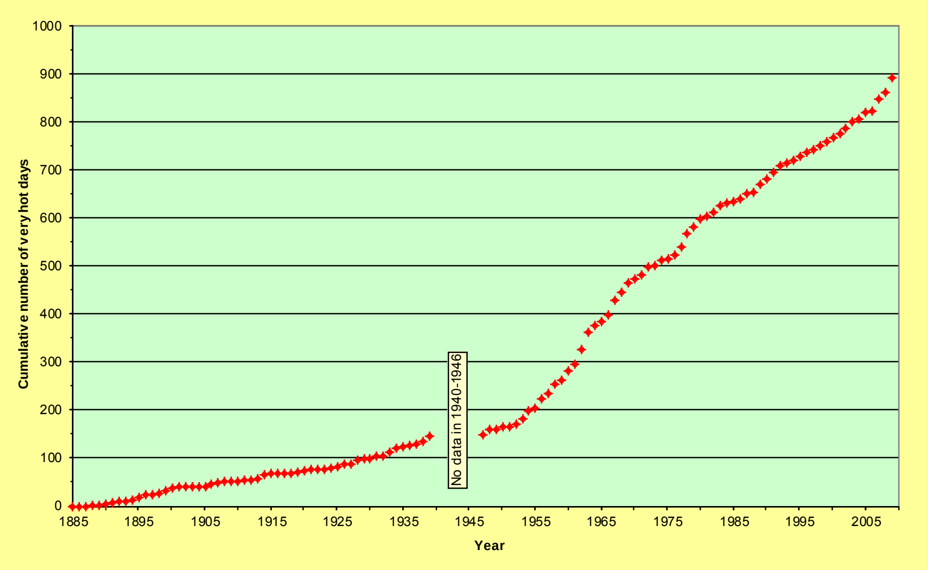


Hong Kong: Warming trend 1885-2009

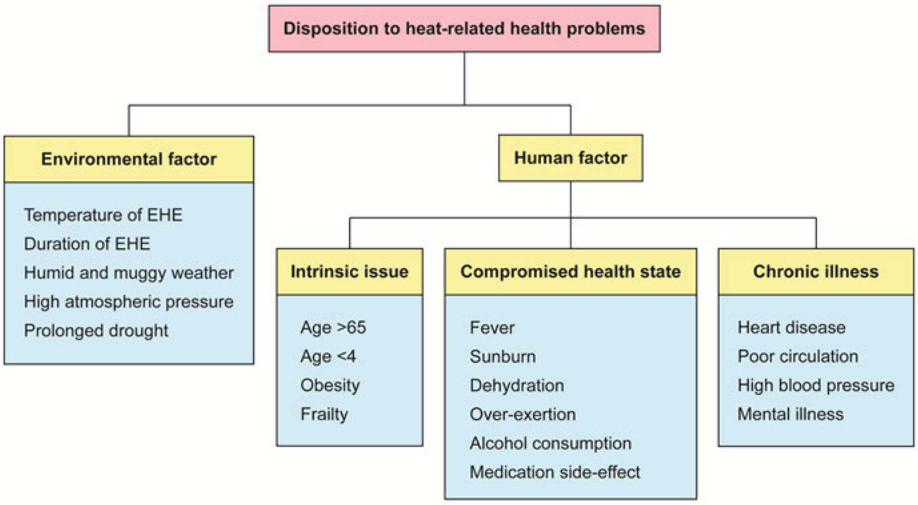
Urban heat island effect



Very hot days in Hong Kong: 1885-2009

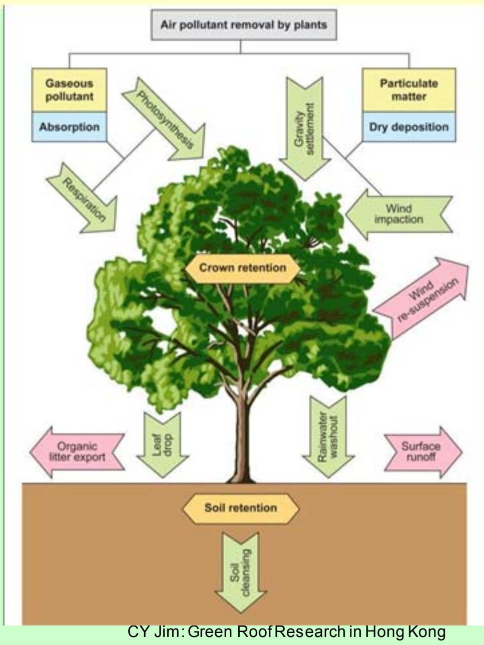


Heat-related health problems



Green roof benefits and functions

Air pollutant: Plant removal



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Green roof: Air pollutant removal

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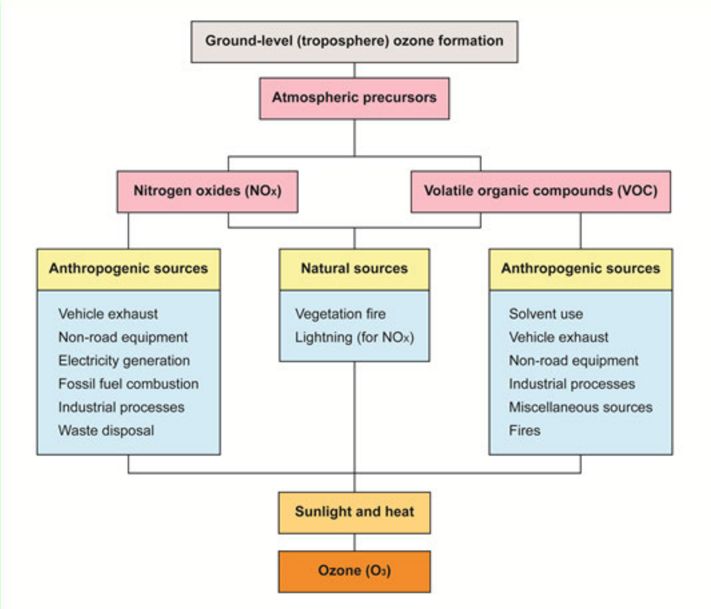
Ground-level ozone formation



Green roof: Water movement

Outdoor recreation & visual amenity

Wildlife habitat & noise abatement

Green roof promotion and policies

Policies and incentives

1. Demonstration green roof sites
2. Technical information centre
3. Technical assistance
4. Green roof as an integral part of urban greening programme and sustainable development
5. Financial subsidies to home owners (rate rebate)
6. Stormwater charge (impermeable surface fee)
7. Gray water collection and use
8. Green roof award of excellence

Green roof promotion and policies

Regulatory framework

1. Removal of institutional barriers
2. Adjustment of land, planning, building and related development and safety regulations
3. Contractor and worker certification programme
4. Green roof standards and sample specifications
5. Planning approval condition
6. Green building guidelines
7. Green roof exemption from GFA calculation
8. Statutory requirement

Green roof promotion and policies

Publicity and public education

1. Green Roof Research and Application Centre
2. Platform for sharing of information and experience
3. Seminars and workshops
4. Training programmes
5. Posters, leaflets, booklets, API, website
6. Supply correct and modern green roof knowledge and technology
7. Overcome misconceptions and psychological barriers
8. Emphasis on environmental and energy conservation benefits

The End

Questions and Comments are Welcome