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REVIEW

Effects of Evapotranspiration on Mitigation of Urban Temperature by Vegetation and Urban Agriculture

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Abstract

The temperature difference between an urban space and surrounding non-urban space is called the urban heat island effect (UHI). Global terrestrial evapotranspiration (ET) can consume 1.4803×10^{23} joules (J) of energy annually, which is about 21.74% of the total available solar energy at the top of atmosphere, whereas annual human energy use is 4.935×10^{20} J, about 0.33% of annual ET energy consumption. Vegetation ET has great potential to reduce urban and global temperatures. Our literature review suggests that vegetation and urban agricultural ET can reduce urban temperatures by 0.5 to 4.0°C. Green roofs (including urban agriculture) and water bodies have also been shown to be effective ways of reducing urban temperatures. The cooling effects on the ambient temperature and the roof surface temperature can be 0.24-4.0°C and 0.8-60.0°C, respectively. The temperature of a water body (including urban aquaculture) can be lower than the temperature of the surrounding built environment by between 2 and 6°C, and a water body with a 16 m^2 surface area can cool up to 2 826 m^3 of nearby space by 1°C. Based on these findings, it can be concluded that the increase of evapotranspiration in cities, derived from vegetation, urban agriculture, and water body, can effectively mitigate the effect of urban heat islands.

Key words: evapotranspiration, urban heat island, vegetation, temperature

INTRODUCTION

Urbanization and the conversion of the earth's surface to urban uses represent major change in global land use and have considerable impact on the environment (Weng and Yang 2004). The global urban population has risen rapidly from 13% in 1900 to 46% in 2000 and is likely to reach 69% by 2050. At the same time, the urban thermal environment has been worsening in recent decades due to rapid development and increased heat discharge from vehicles and buildings (Haider 1997; Argiro and Marialena 2003). Urban areas tend to experience relatively higher temperatures compared to the surrounding countryside. The difference between temperatures measured in an urban space and those measured in the surrounding non-urban green space is called the urban heat island effect (UHI) (Oke 1987).

Several studies have revealed that the heat island effect is mainly related to the high density of buildings and urban structures that absorb solar radiation, the use of highly absorbent materials, the lack of green spaces, the characteristics of urban canyons, and the production of anthropogenic heat (Oke *et al*. 1991). A heat island can occur at a range of scales. It can manifest itself around a single building (Thurow 1983), a

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small vegetative canopy (Taha *et al*. 1989, 1991) or over a large area of a city. Worldwide deforestation, sprawling urbanization and the loss of fertile agricultural land have reduced plant cover and evapotranspiration (ET). A decrease in ET causes a reduction in latent heat consumption. Therefore, more energy becomes available as sensible heat, which then causes higher land surface temperatures that can contribute substantially to the urban heat island effect and, ultimately, global climate change (Schimidt 2010). The heat island intensity can result in up to a 10°C temperature difference between the dense urban area and the surrounding rural zones (Santamouris *et al*. 2001). Higher urban temperatures can increase energy use, mostly due to a greater demand for air conditioning, and as power plants burn more fossil fuels, they drive up both pollution levels and energy costs (Weng and Yang 2004). There is, therefore, a pressing need to evaluate strategies that can mitigate further increases in urban temperatures (Bowler *et al*. 2010).

Urban vegetation has the potential to moderate air temperature not only through shading and absorbing solar radiation for photosynthesis, but also through the cooling effects of ET (McPherson *et al*. 1994; Wong *et al*. 2003; Shashua-Bar *et al*. 2009). The ET of urban green area that exceeds 14 ha, can bring about obvious cooling effect of heat island (Lu *et al*. 2012). The rooftop with 6% vegetation coverage can result in a reduction of 1 to 2°C, and green roof has been considered to be a powerful tool to mitigate urban heat island effect and save energy consumption for air-conditioning (Peck 2003; Mazereeuw 2005; Saiz *et al*. 2006). Especially, the development of urban agriculture, in the form of community gardens, roof gardens (green roofs), and backyard gardens, significantly increases urban ET by means of increasing urban green area and helps reduce air temperature in cities (Mazereeuw 2005; Saiz *et al*. 2006; Shashua-Bar *et al*. 2009). The purpose of this study was to review the roles of evapotranspiration from urban greening (including vegetation, urban agriculture, urban aquaculture, and water body) on alleviating urban heat island effect, based on research results from this investigation and from previous publications. Such results can provide useful information for urban design and planning including urban agriculture and greening.

EFFECT OF VEGETATION ET ON URBAN HEAT ISLANDS (UHIs)

According to this study's calculations, annual global terrestrial ET can consume 1.4803×10^{23} J of energy, about 21.74% of total available solar energy at the top of atmosphere, whereas annual human energy use is 4.935×10^{20} J, which is about 0.33% of annual ET energy consumption (Appendix). This result indicated that it should be possible to substantially reduce urban and global temperatures by increasing ET. Many researchers have suggested that urban greening may be employed as a strategy for combating the ill effects of UHIs (Wong 2002; Alcazar and Bass 2005; Mackey *et al*. 2012). The cooling effect induced by green areas can improve the thermal comfort of densely populated cities, as well as the overall health and living conditions of their inhabitants (Pompeii II *et al*. 2012). Vegetation and urban materials differ in their moisture, aerodynamic and thermal properties, so urban greening could affect temperatures *via* different processes (Oke 1989; Givoni 1991). When considering the effects of vegetation on the outdoor thermal environment and landscape design, there are generally three kinds of plants involved: trees, shrubs and grasses (Lin *et al*. 2008). Trees are more efficient at improving microclimatic environments than grasses and shrubs. The microclimatic effect of trees occurs through a number of processes (Dimoudi *et al*. 2003): (1) reduction of solar heat gains on windows, walls, and roofs through shading; (2) reduction in a building's long-wave exchange with the sky as the building surface temperatures are lowered through shading; (3) reduction in the conductive and convective heat gains by lowering dry-bulb temperatures through evapotranspiration during summer; and (4) increasing evaporative cooling by adding moisture to the air through evapotranspiration.

During the past few decades, a number of studies have investigated the cooling effects of urban green areas. Some of the studies are summarized in Table 1. According to Table 1, high temperature regions were found in densely built environments. Vegetation in the urban environment can greatly improve the urban microclimate, as well as mitigate the heat island effect, by reducing air temperatures during summer. Studies

Table 1 Summary of recent studies related to cooling effects of vegetation on urban heat island

Location & country	Climate type	Season	Green site and comparator	Features of green site	Air temperature difference	Influence area	Reference
Haifa, Israel	Mediterranean		Park to its surrounding	0.5 ha		20-150 m	Givoni (1972)
Mexico City, Mexico	Savanna tropical	Dry season	Park to its surrounding	~500 ha	2-3°C (clear night)	2 km	Jauregui (1990)
Tokyo, Japan	Monsoon temperate		Green area to its surrounding	300-700 m wide		Leeward 200 m	Honjo and Takakura (1991)
Kumamoto, Japan	Humid temperate	Aug-Sep	Green area to its surrounding	60 m×40 m small green area	3°C		Saito *et al*. (1991)
Montreal, Canada	Temperate continental		Urban parks to built areas		2.5°C		Gao (1993)
Tokyo, Japan	Monsoon temperate	Summer	Vegetated to non-vegetated zones		1.6°C		Gao (1993)
Tama New Town, Japan	Humid temperate	Aug-Sep	Park to nearby urban sites	0.6 km^2 grass field	1.5°C (noon time)	Leeward 1 km	Ca *et al*. (1998)
Tel-Aviv, Israel	Mediterranean	Jul-Aug	11 urban green areas with trees to its surroundings	450-11 025 m^2	1.3-4.0°C (daily max at 15:00)		Shashua-Bar and Hoffman (2000)
Gaborone, Botswana	Savanna tropical	Summer	Oasis to open fields of bare soil		2°C (daytime)		Jonsson (2004)
Tel-Aviv, Israel	Mediterranean	Summer	Urban park to built-up area	Trees with a wide canopy	3.5°C (daytime)		Potchter *et al*. (2006)
Tokyo, Japan	Monsoon temperate	Summer	Park to its surrounding	One of the largest parks in Tokyo	1°C (9:00-15:00)		Sugawara *et al*. (2006)
Hong Kong, China	Monsoonsubtropical	Summer	Tree cover to shrub cover areas		0.5-1°C		Giridharan *et al*. (2008)
Nagoya, Japan	Monsoon temperate	July	Park to its surrounding	147 ha; wooded parkland (60%); cemetery (40%)	1.9°C (max)	200-300 m	Hamada and Ohta (2010)

have shown that the larger the green area, the lower the air temperature in the surroundings that are influenced by the green space. In addition, the surrounding area located downwind from the green space was more likely to be influenced by the green area, and strong winds usually intensified the cooling effect of the green area. Table 1 indicates that the vegetation in urban areas can reduce the surrounding air temperature by 0.5-4.0°C. Mackey *et al*. (2012) suggested that vegetation can significantly reduce temperatures when the normalized difference vegetation index was larger than 0.35. Thus, the vegetation in urban areas can be an effective way of mitigating the heat island effect.

Urban agriculture is one important part of urban vegetation, which can produce significant environmental benefits such as mitigation of urban heat island and reduction of greenhouse gas emissions, as well as improvement of air quality (Mazereeuw 2005; Shashua-Bar *et al*. 2009). Yokohari *et al*. (1997) studied the effect of paddy fields on air and surface temperatures in urban fringe areas in Tokyo, Japan, and found that the paddy field with high coverage ratio and low segmentation ratio had the maximum temperature reduction relative to the urban built-up area. Yang *et al*. (2004) reported that the average land surface temperature in rice paddies (urban agriculture area) was 2.87°C lower than the overall average temperature. It was also found that a 0.1 increase of normalized difference vegetation index can reduce land surface temperature by 1.3°C, and that of normalized difference moisture index can reduce land surface temperature by 1.7°C. It demonstrated that vegetation coverage and surface moisture content greatly influenced land surface temperature (Yang *et al*. 2004). Furthermore, urban agriculture has also brought about a significant economic benefit. A US$ 1 investment in food-growing project in urban areas can yield a US$ 6 of production (Doron 2005). In Asian and Latin American cities, about 10-30% of fruit and vegetables consumed are locally produced within the cities. Singapore grows 25% of all the consumed vegetables in urban areas. Urban agriculture in Hong Kong meets 45% of vegetable demand, and one third of agricultural output in USA comes from urban/metropolitan areas (Doron 2005). Most surprisingly, Shanghai and Beijing in China are fully self-sufficient in vegetables (Hough 2004). Therefore, in comparison to traditional rural agriculture with large environmental costs such as pesticides, fertilizers, and herbicide use, as well as energy consumption for shipping to city, urban agriculture provides fresh and organic food to the city consumers and is a more sustainable food production system with economic benefit and environmental benefits (Smit and Nasr 1992; Broadway 2009; Camerona *et al*. 2012).

EFFECT OF GREEN ROOFS ON UHIs

Green roofs can increase evapotranspiration, reduce energy demand for space climate conditioning (through the direct shading of the roof), and improve insulation values (Liu and Baskaran 2003). If widely adopted, green roofs can reduce both the urban heat island effect and urban energy consumption. The use of green roofs has been known since ancient times, in both hot and cold climates (Renato *et al*. 2005). Today, they are increasingly used to alleviate environmental problems associated with the urban heat island effect (Jim and Tsang 2011). A green roof involves growing low-maintenance, hardy plants, such as sedum, along with grasses and other smaller plant species on top of an existing roof membrane (Cravitz 2006). There are different types of green roofs. Dunnett and Kingsbury (2004) divided green roof technologies into two categories: extensive and intensive. Intensive green roofs generally require more plant care, whereas extensive roofs required less. Intensive green roofs also emphasize the use of space and therefore raise higher aesthetic expectations than more functional, extensive green roofs. Intensive green roofs generally need a deeper substrate, contain greater plant diversity, including trees and shrubs, and require a regular watering schedule. Therefore, they cost more to maintain than extensive roofs.

Table 2 summarizes the key findings from the literature review that relate to the cooling effect and energy cost reductions that can be expected from green roofs. Generally, ambient temperature and roof surface temperature are the two cooling effects in which scientists are interested. Ambient temperature has an influence on the human body, as a moderate air temperature makes people feel comfortable. The cooling effects on the ambient temperature and the roof surface temperature were between 0.24 and 4°C. The lifespan of a roof is related to roof surface temperature, and researchers have generally accepted the opinion that a roof's durability can be doubled if an appropriate green roof is installed (Robitu *et al*. 2004). Green roofs are found throughout many European countries, such as France, Germany and Switzerland. They are also rapidly gaining popularity across other parts of the world. In the United States, Portland, Oregon pioneered an incentive program (Clean Air Incentive and Discount Program) to encourage installing green roofs on commercial, industrial, institutional, and residential properties (Liu and Baskaran 2003). Research into green roofs has been undertaken throughout the world, but they have mainly been put into practice in developed countries.

Compared to ambient temperature, the cooling effect of a green roof on surface temperature is between 0.8 and 60°C, which is much larger than the cooling effect caused by ambient temperature alone. This may be due to the properties of different roofs and albedo, the specific site location, various climate types, the total area of a green roof, the plant species present on the green roof, etc. (Sailor 1995). Onmura *et al*. (2001) investigated the evaporative cooling effects of roof lawn gardens planted in non-woven fabric as a way of improving passive cooling. Field measurements during summer showed that the amount of heat transferring to the interior was reduced by a roof lawn garden. The surface temperature of the roof slab decreased from about 60 to about 30°C during daytime. The evaporative cooling effect from roof lawn gardens is thought to play an important role in reducing heat flux. Bass *et al*. (2002) used a mathematical model to quantify the mitigation of the urban heat island in Toronto, Canada. Results showed that 50% green roof coverage produced a 1°C reduction in low level air temperatures, while irrigation of the green roofs had a 2°C cooling effect.

Energy cost reductions are also summarized in Table 2. According to Wong (2002), a study in Tokyo showed that if the temperature in Tokyo fell by 0.8°C, as a result of roof top gardens, electric bill savings, equivalent to approximately US$ 1.6 million per day, could be achieved. The Japanese magazine, *Nikkei Architecture*, published a book about green roofs in 2007, showing that the effect of 4 m^2 grass was equivalent to an air-conditioning system, so the energy saving associated with a green roof was significant. Alcazar and Bass (2005) also compared the energy performance of dif-

Table 2 Summary of the key findings from literature review related to cooling effect and energy cost reduction of green roofs

Study[1)]	Location	Cooling effect (°C)		Energy cost reduction
		Ambient temperature	Roof surface temperature	
Onmura *et al*. (2001)	Osaka, Japan		30-60	
Niachou *et al*. (2001)	Loutraki, Greece	2		
Wong (2002)	Singapore	4		
	Tokyo, Japan	0.8		Electric-bill savings equivalent to approximately US$1.6 million d^{-1}
Kravitz (2006)	USA		32-43	Double the life span of roof
Sonne (2006)	Central Florida, USA		7-22	
	A gymnasium in Toronto		⩾1.6	
Takebayashi and Masakazu (2007)	Kobe University, Japan		10	
Wu *et al*. (2008)	Shenzhen, China		0.8-7.9	
Alar *et al*. (2009)	Tartu, Estonia		3.4	
Pompeii II (2010)	Chicago's City Hall, USA	0.2-1.8	4-21	
Zhang *et al*. (2010)	Shanghai, China		3.29	Reduce the energy consumption of the air-conditions by 18%
Susca *et al*. (2011)	New York City, USA	2		
Bass *et al*. (2002)	Toronto, Canada	1-2		
Alexandri and Jones (2008)	Riyadh, Saudi Arabia		12.8	
	Mumbai, India		26.1	
	Moscow, Russia		9.1	
	London, UK		19.3	
Salah *et al*. (2011)	La Rochelle, France		30	

[1)] Studies by Bass *et al*. (2002), Alexandri and Jones (2008) and Salah *et al*. (2011) are based on model simulations.

ferent roofing systems. The study showed that installing a green roof on a building provided savings in annual and peak energy consumption. The green roof resulted in a total annual energy consumption reduction of 1%, with a 0.5% reduction when heating the building and a 6% reduction when cooling it.

Many studies have shown cooling effects of green roofs and reduced energy costs. Cooling effects depend on several factors, and the heat island effect can be alleviated by various types of green roofs where overall efficiency may be enhanced by artificial and intensive management. So a "best practices" guide on how to create a green roof and how to increase its benefits should be created. "Greening" buildings can be used to create more comfortable air temperatures in cities and improve the microclimate around structures.

In China, large green roofs are rare. A study in Hong Kong demonstrated that the top three barriers to installing green roofs were "lack of promotion from the government and social communities in the public and private sectors", "lack of incentives from the government aimed at the owners of the existing buildings" and "increased maintenance costs" (Zhang *et al*. 2012). Barriers exist in the entire building life-cycle process, including planning and design, construction and the operation and management stages. However, there have been a few trial projects in China, and the advantages of such extensive green roofs were significant (Kuesters 2004). Although they are moving into the mainstream at a considerable rate, green roofs remain an unknown commodity to the owners, managers and contractors of many buildings (Yanic 2011). To solve this problem, the related standards and regulations first need to be addressed.

The main obstacle to green roof is the cost of its installation and maintenance. However, the green roofs with agricultural production can bring a good economic benefit (Nowak 2004). Rooftop agriculture is one way in which urban areas could attempt to be more balanced and sustainable in their resource consumption. It is possible to produce a variety of fruit, grain, and vegetable crops on rooftops, either in containers or as field crops (TFPC 1999). For example, a rooftop garden was established in Josiah Quincy School, Boston. Children, along with neighboring seniors, harvest strawberries, tomatoes, beans, radishes, and watermelons, and green roof agriculture can bring a significant economic and social benefits (Sheung 2001; Huang 2010). Dai *et al*. (2011) analyzed present situation of roof agriculture with 500 m^2 in Shilipu Community in Wuhan City, discussed common key technology of Wuhan roof agriculture, and put forward some corresponding suggestions for the construction of roof agriculture in Wuhan City. The cost-benefit analysis of green roofs also requires to taking the environmental benefits into account through life cycle assessment (Saiz *et al*. 2006; Kulak *et al*. 2013). By replacing common flat roof with a green roof, environmental impacts are reduced by 1-5.3%, and energy savings for cooling in peak hour in the upper floors reach up to 25% (Saiz *et al*. 2006). Thus, integrating green roofs with urban agriculture has great potential to develop, especially considering their environmental and cooling benefits.

EFFECT OF WATER BODIES ON UHIs

Water bodies in urban areas have a major influence on the UHI effect due to the thermal properties of water and evaporation. Table 3 summarizes the effects of a water body on urban temperatures in four cities: Beijing and Shanghai, China; Indianapolis, USA; and Tel-Aviv, Israel. Usually the temperature of a water body is lower than the temperature of the surrounding built-up area, and the differences between them can be 2-6°C. This proves that urban water bodies have a great influence on the urban climate. A study in Bucharest showed that the cooling effect of a pond with an area of 4 m^2 was about 1°C at a height of 1 m, measured at 30 m distance (Robitu *et al*. 2004). Consequently, a water body with a 16 m^2 surface area should cool a 2 826 m^3 space by 1°C. The evaporation of water surface provides an important counteract to the Urban Heat Island effect, in combination with use of light-colored surfaces and vegetated surfaces (Spronken-Smith and Oke 1999; Chang *et al*. 2007). There are relative large areas of reservoirs in many cities such as Beijing, Wuhan and Shenzhen. Urban aquaculture in ponds and reservoirs in cities can not only provide fish food, but also help mitigate the Urban Heat Island effect due to large areas of water bodies. The most notable approach consists of stocking fish in reservoirs and large urban water bodies, followed by recapture after a period of 1-2 years. Culture-based fisheries in Donghu Lake in Wuhan City, China, are dependent on stocking millions of silver carp and bighead carp seed, and, fish production increased from 180 t in 1971 to 1 840 t in 1995, owing to enhanced management (Liu and Cai 1998). The area of water body in Donghu Lake reaches up to 1 500 ha, which has a significant cooling effect for Wuhan City as a very hot city in summer.

Table 3 Effects of water body on urban temperature

City	Name of water body	Area (km^2)	T of water body (°C)	T of land (°C)	Turning T (°C)	Turning distance (m)	Distance from downtown (km)	Reference
Beijing (China)	Miyun	98.68	26.44	32.86	27.74	2 500	82	Sun *et al*. (2012)
	Huairou	7.07	27.3		30.43	2 000	55	
	Shisanling	1.89	27.12		30.34	1 200	40	
	Shahe	2.82	26.53		29.35	800	30	
	Hongluohu	0.48	28.17		30.03	450	48	
	Yanxihu	2.49	27.29		28.91	400	50	
	Kunminghu	2.36	28.68		33.52	900	14	
	Yuanmingyuan	0.67	30.35		33.78	500	13	
	Shichahai	2.26	30.92		34.36	500	0	
	Yuyuantan	0.46	29.05		34.89	1 100	8	
	Wenyuhe	9.46	28.09		30.45	900	20	
	North Canal	10.01	28.5		29.9	1 000	30	
	Qinghe	1.16	31.24		33.11	800	25	
	Huaishahe	2.47	26.56		27.79	900	50	
	Jingmi Channel	3.89	28.23		28.93	500	40	
Beijing (China)		146.2	28.3	32.86	30.9	963		Sun *et al*. (2012)
Shanghai (China)	Yinchu Lake	14.3×10^{-2}	26.4	29.6			0	Kai *et al*. (2004)
	Chaoyang	2×10^{-2}	22.4	25.6				
	Taipingqiao	1.2×10^{-2}	5.8	7.1				
	New Hongqiao	1×10^{-2}	22.9	24.8				
	Zhangjiabang		35.5	37.6				
	Suzhou River		34.3	35.4				
Indianapolis (USA)			25.05	32.4				Weng *et al*. (2004)
Tel-Aviv (Israel)		42-84 km^2	9.7	18.5				Saaroni *et al*. (2000)

T, temperature; T of water body, the average temperature of the water body; Turning T, the temperature at the turning distance; Turning distance, the measure for the urban temperature changing scope influenced by water body.

CONCLUSION

Annually, global evapotranspiration (ET) can consume 1.483×10^{23} J of energy, which is about 21.74% of the total available solar energy, whereas annual human energy use is 4.935×10^{20} J, which is about 0.33% of the annual ET energy consumption. Thus, ET shows considerable potential to reduce urban temperatures. This review of past studies indicates that vegetation ET can reduce urban temperatures by 0.5-4.0°C. The cooling effects of green roofs on ambient temperature and roof surface temperature can range between 0.24-4.0°C and 0.8-60.0°C, respectively, and the lifespan of a roof can be doubled by installing an appropriate green roof. The temperature of water body is 2-6°C lower than that of the surrounding built environment area. A water body with an area of 16 m^2 can cool 2 826 m^3 of surrounding space by 1°C. The development of urban agriculture including community gardens, roof gardens (green roofs), backyard gardens, and aquaculture, can intensify the mitigation of urban heat island effect. These results strongly suggest that increasing evapotranspiration in cities can mitigate the effect of urban heat islands, which can provide some reference for urban planning and design such as the distribution of urban greening including urban agriculture and water boby, on aspects of cooling urban temperature and improving urban heat environment.

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Appendix associated with this paper can be available on http://www.ChinaAgriSci.com/V2/En/appendix.htm

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