Phenology acts as a primary control of urban vegetation cooling and warming: A synthetic analysis of global site observations

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ABSTRACT

Urban vegetation can influence local air temperatures through its biophysical effects on surface energy balance. These effects produce gradients (ΔT_a) between air temperature of vegetation spaces (T_{veg}) and air temperature of open spaces (T_{open}) ($\Delta T_a = T_{veg} - T_{open}$), hereafter referred to as vegetation cooling (negative values of ΔT_a) and warming (positive values of ΔT_a), respectively. But vegetation cooling or warming highly depends on background climate of urban areas as well as on vegetation states. Field observations are usually restricted to one or few cities, setting limitations to a general understanding. In this study, a synthetic analysis of 3634 point-scale in-situ observations from 77 global sites in 35 cities was conducted using the bootstrap sampling and hierarchical partitioning methods. Results show that vegetation cooling is generally stronger during the daytime periods, in warm seasons, at low latitude zones, for forest lands and at leaf growth stage, while vegetation warming usually occurs in the opposite contexts. Urban vegetation begins to exert considerable cooling effects when the daily mean background air temperature (BAT) is $>10.0^\circ\text{C}$, but on average has a slight warming effect when BAT is $<10.0^\circ\text{C}$. Besides, vegetation cooling increases sharply when evapotranspiration is $>61.7\text{ mm/month}$ or when area of urban vegetation is $>35.2\text{ ha}$. Plant growth stages (i.e., canopy leaf growth, senescence and dormancy stages) ($37.6 \pm 0.11\%$), a vegetation phenology proxy, acts as the primary biotic factor, while seasonality ($23.0 \pm 0.11\%$) and latitude ($11.4 \pm 0.07\%$) that control the background climate are two most important abiotic contributors. Our findings suggest approximate thresholds for distinguishing vegetation cooling/warming effects and provide helpful information for future urban greenspace planning aimed at mitigating local climate warming.

1. Introduction

Recently, there has been growing interest in mitigation of increased air temperature impacts on human health (Wolff et al., 2018; Su et al., 2019). Vegetation is commonly believed to considerably regulate local air temperatures (Ellison et al., 2017; Su et al., 2019). However, nearly 88% of global primary vegetation-covered land in urban areas has been destroyed and replaced by artificial surfaces in urbanization processes

during the past decades (Seto et al., 2012; d'Amour et al., 2016). This trend, in turn, has intensified urban climate warming locally (Sun et al., 2016). Additionally, more than 1.2 million km^2 of global lands have a high probability ($>75\%$) of being converted into urban areas by 2030 (Seto et al., 2012). Along with global climate warming, the local climate in urban regions will increase in the future (Nakayama and Fujita, 2010; Escobedo et al., 2011; Oliveira et al., 2011).

Urban vegetation can influence local air temperature (T_a) through

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Acronyms

T_a :	air temperature;
T_s :	surface temperature;
T_{veg} :	air temperature of vegetation spaces;
T_{open} :	air temperature of open spaces;
BAT:	background air temperature of urban areas;
ΔT_a :	published gradient between T_{veg} and T_{open} ;
ΔT_a^* :	normalized gradient between T_{veg} and T_{open} ;
$\odot$:	downward solar shortwave radiation ($W m^{-2}$);

MAP:	Mean annual precipitation (mm/year);
NDVI:	Normalized Difference Vegetation Index;
EVI:	Enhanced Vegetation Index;
LAI:	Leaf Area Index;
PGS:	Plant Growth Stage;
S:	area of urban vegetation (ha);
ET:	evapotranspiration (mm/month)
$ET_{in-situ}$:	monthly ET calculated from in situ data (mm/month)
ET_{MODIS} :	monthly ET extracted from MODIS products (mm/month)

its effects on the surface energy balance (Cao et al., 2010a,b; Chen et al., 2012; Su et al., 2019), i.e., the so-called biophysical effect (Lee et al., 2011; Zeng et al., 2017), which is currently an active area of research with a myriad of practical applications (Oke, 1989; Bounoua et al., 2002; Georgi and Zafiriadis, 2006; Chang et al., 2007; Shashua-Bar et al., 2010; Oliveira et al., 2011; Susca et al., 2011; Chen et al., 2012). This effect produces gradients (ΔT_a) between the air temperature of vegetation spaces (T_{veg}) and air temperature of open spaces (T_{open}) ($\Delta T_a = T_{veg} - T_{open}$), hereafter referred to as vegetation cooling and warming for negative and positive values of ΔT_a , respectively. The background climate in cities as well as vegetative functions have been investigated as two key forces for vegetation cooling and warming (Spronken-Smith and Oke, 1998; Su et al., 2019). The evaporative cooling of vegetation (Taha et al., 1991; Dimoudi and Nikolopoulou, 2003; Jonsson, 2004; Bowler et al., 2010; Zhao et al., 2014; Feyisa et al., 2014), and shading of vegetation canopy which produces shade on understory spaces and regulates the incoming/outgoing solar shortwave and infrared and longwave radiation (Oke, 1989; Pearlmutter et al., 1999; Dimoudi and Nikolopoulou, 2003; Bowler et al., 2010; Feyisa et al., 2014) are two most important functions inducing vegetation cooling. Low albedo of vegetation leads to a strong daytime radiative warming (Lee et al., 2011). Furthermore, vegetation usually causes turbulence which brings heat from aloft to the near surface at nighttime and thereby generates nighttime warming (Lee et al., 2011). Background climate can influence the vegetation cooling and warming by controlling the directions of heat transfer (Zhang et al., 2013; Zhao et al., 2014; Li et al., 2015; Su et al., 2019), which changes the sensible heat fluxes and longwave radiation (Eq. (14), Zeng et al., 2017) and in turn the surface energy balance (Cao et al., 2010a,b; Chen et al., 2012; Su et al., 2019).

In contrast to satellite-based observations that record land surface temperatures (T_s) associated with surface energy budget (Bonan, 2008; Cao et al., 2010a,b; Lee et al., 2011; Peng et al., 2014; Zhang et al., 2014; Li et al., 2015; Alkama and Cescatti, 2016), field observations focus on T_a , which is a more reasonable climatic and environmental indicator controlled by atmospheric mixing and used to characterize urban climate warming that requires closer attention (Su et al., 2019). Currently, the vegetation cooling and warming on local T_a has been extensively studied worldwide using time-series field observations worldwide (Georgi and Zafiriadis, 2006; Potchter et al., 2006; Chang et al., 2007; Zhang et al., 2013; Su et al., 2019). For example, Dhakal and Hanaki (2002) reported that vegetation close to buildings lowers T_a maximally by 0.47 °C in Tokyo. Meier (1991) observed a more enhanced cooling effect ($\Delta T_a = -1.7$ °C) of vegetation on T_a in California. Jauregui (1991) and Wong and Yu (2005) detected a larger cooling magnitude of -3.0 °C to -4.0 °C in the tropical cities of Mexico and Singapore, from 1984 to 1987 and 1961 to 1963, respectively. Taha et al. (1991) also observed that urban vegetation produced a 6.0 °C lower T_a than in the surrounding environment during October of 1986 in Davis. A net warming of vegetation was also reported in some studies, e.g. Taipei ($\Delta T_a = 4.5$ °C) (Chang et al., 2007) and Arava Valley ($\Delta T_a = 2.2$ °C) (Potchter et al., 2012). However, most field studies were limited to one or few cities (Wong and Yu, 2005; Bowler et al., 2010; Feyisa et al., 2014), while at global scale the direction and magnitude of ΔT_a were highly variable among cities (Georgi and Zafiriadis, 2006; Shashua-Bar et al., 2009; Su et al., 2019). A synthetic analysis to generalize these point-scale results from global site observations is greatly warranted. In addition, uncertainty remains as to which of the underlying factors control the background climate, evaporative cooling and canopy shading of vegetation in urban regions. Studies of cross-regional

Fig. 1. Location of global published in-situ observation sites.

Table 1
Data of global site in-situ observations.

No.	Longitude	Latitude	City	Period	Record Quantity	Forest Type	BAT (°C)	MAP (mm)	Average ΔT (°C)	References
1	23.72	37.9	Athens	11-Jul,2005–31-Jul,2005	91	Tree block	36.13	1362.17	−2.14	Zoulia et al. (2009)
2	23.74	37.97		Oct. 2006–Jun,2007	45	Tree block	28.9	400	−0.12	Shashua-Bar et al. (2010)
3	116.39	39.37	Beijing	Jun, 2006–Jul,2007	83	Tree block, Grass	31.1	483.9	−0.21	Liu et al. (2008)
4	116.42	39.87		Jun–Aug	37	Tree block, Grass	27.43	483.9	−3.41	Li et al. (1999)
5	116.33	39.93		Jul,2010	64	Tree block	35.68	630	−2.03	Yan et al. (2012)
6	116.27	39.97		11–20, Jul, 2010	10	Tree row	28.8	626	−0.62	Ji et al. (2012)
7	116.35	40		Aug–Oct, 2006	78	Tree row, Grass	21.1	731.7	−0.6	Ma and Li (2007)
8	116.37	40		11–20, Jul, 2010	5	Tree row	28.8	626	−0.82	Ji et al. (2012)
9	116.4	40		11–20, Jul, 2010	5	Tree row	28.8	626	−1.22	Ji et al. (2012)
10	116.4	40.02		11–20, Jul, 2010	5	Tree row	28.8	626	−1.18	Ji et al. (2012)
11	116.26	40.03		11–20,Jul,2010	5	Tree row	28.8	626	−0.84	Ji et al. (2012)
12	116.42	40.05		Jan–Oct,2011	100	–	20.55	483.9	−0.71	Ji et al. (2013)
13	116.09	40.06		29-Jul,2010–28,Mar,2011	192	Grass	26.88	630	−0.64	Wu et al. (2009)
14	116.35	40.25		11–20,Jul,2010	5	Tree row	28.8	626	−1.08	Ji et al. (2012)
15	116.4	40.58		11–20,Jul,2010	45	Tree block, Grass	31.8	626	−2.74	Zhu et al. (2011)
16	31.27	30.04	Cairo	Jun, 2009	9	Tree block	41	26	−5.77	Mahmoud. (2011)
17	−121.76	38.54	Davis	12–18, Oct-1986	288	Tree block, Tree row	18.26	2000	−0.67	Taha et al. (1991)
18	112.99	28.13	Changsha	Jan–Dec, 2005	120	Tree row	19.13	1780	−0.21	Luo (2013)
19	112.97	28.24		19–21,Jun,2007	14	Tree block, Tree row, Shrub	35.53	1422.4	−4.07	Zhao et al. (2007)
20	24.02	35.52	Chania-Crete	08–30, Jun, 2005	96	Tree block, Tree row	31.47	640	−3.05	Georgi and Dimitriou (2010)
21	106.62	29.58	Chongqing	–	19	Tree block, Shrub, Grass	36	1200	−5.23	Feng et al. (2008)
22	35.24	30.66	En Yahav	1:00–22:00,07,Feb,2006	75	Tree block, Tree row, Grass	13.45	530.3	0.25	Potchter et al. (2012)
23	11.26	43.78	Florence	2002	24	Tree block	–	679.99	−1.82	Bacci et al. (2003)
24	119.26	26.06	Fuzhou	07–09,Jul,2012	24	Tree block, Grass	38.13	1500	−1.37	Cai et al. (2013)
25	33.44	14.98	Gezira	19–27, Dec, 1964	43	Tree row	26.68	98	−1.9	Davenport and Hudson (1967)
26	11.47	57.7	Goteborg	Apr–Jul, 1994	7	Tree block, Tree row	−2.28	685.58	−4.38	Upmanis et al. (1998)
27	136.92	35.16	Goya	Mar–Oct,2004	33	Tree block	10	560	−2.72	Cao et al. (2010a,b)
28	136.98	35.17	Goya	Aug,2006–Apr,2007	211	Tree row	28.86	1564.6	−0.85	Hamada and Ohta (2010)
29	113.74	23	Guangzhou	12:00, 17 Oct,2009; 1, Jun,2011	2	Tree block	27.65	1366.51	−1.91	Chen et al. (2012)
30	113.23	23.1		12:00, 06 Oct,2005	1	Tree block	33.5	1366.51	−2.94	Su et al. (2010)
31	113.28	23.1		12:00, 06 Oct,2005	1	Tree block	32.67	1366.51	−2.46	Su et al. (2010)
32	113.29	23.11		12:00, 06 Oct,2005	1	Tree block	32.93	1366.51	−4.24	Su et al. (2010)
33	113.23	23.12		12:00, 17 Oct,2009; 1, Jun,2011	2	Tree block	28.51	1366.51	−4.31	Chen et al. (2012)
34	113.34	23.12		12:00, 17 Oct,2009; 1, Jun,2011	2	Tree block	29.08	1366.51	−2.11	Chen et al. (2012)
35	113.23	23.13		12:00, 06 Oct,2005	1	Tree block	32.88	1366.51	−2.91	Su et al. (2010)
36	113.25	23.13		12:00, 17 Oct,2009; 1, Jun,2011	2	Tree block	29.54	1366.51	−3.49	Chen et al. (2012)
37	113.26	23.13		12:00, 06 Oct,2005	1	Tree block	31.92	1366.51	−2.45	Chen et al. (2012)
38	113.29	23.13		12:00, 17 Oct,2009; 1, Jun,2011	2	Tree block	28.27	1366.51	−2.51	Chen et al. (2012)
39	113.37	23.13		12:00, 17 Oct,2009; 1, Jun,2011	2	Tree block	27.42	1366.51	−2.86	Chen et al. (2012)
40	113.27	23.14		12:00, 17 Oct,2009; 1, Jun,2011	2	Tree block	28.36	1366.51	−2.54	Chen et al. (2012)
41	113.3	23.14		12:00, 17 Oct,2009; 1, Jun,2011	2	Tree block	26.92	1366.51	−1.85	Chen et al. (2012)
42	113.31	23.14		12:00, 06 Oct,2005; 17 Oct,2009; 1, Jun,2011	3	Tree block	29.52	1366.51	−2.90	Chen et al. (2012), Su et al. (2010)
43	113.27	23.15		12:00, 06 Oct,2005	1	Tree block	31.75	1366.51	−3.01	Su et al. (2010)
44	113.28	23.15		12:00, 17 Oct,2009; 1, Jun,2011	2	Tree block	28.09	1366.51	−4.25	Chen et al. (2012)
45	117.27	32.06	Hefei	8:00–20:00,08,Jun,2003;2:00–22:00, 01,May,2005	44	Tree row	29.19	1035.3	−1.17	Liu (2004)
46	111.7	40.8	Inner Mongolia	8:00–20:00, 27, Apr,2003	21	Tree block, Grass	22.64	615.3	−2.82	Ma et al. (2010)
47	101.69	3.15	Kuala Lumpur	–	3	–	–	2260.42	−2.17	Ahmad (1992)

(continued on next page)

Table 1 (continued)

No.	Longitude	Latitude	City	Period	Record Quantity	Forest Type	BAT (°C)	MAP (mm)	Average ΔT (°C)	References
48	130.7	32.81	Kumamoto	–	1	–	–	1484.94	–3	Hamada and Ohira (2010)
49	–9.14	38.72	Lisbon	08, Sep, 2006–08, Mar, 2007	32	Tree block, Tree row	37.3	1000	–2.79	Oliveira et al. (2011)
50	–100.3	25.74	Mexico City	Jul, 1988–1989	1	Tree block	–	748	–2.2	Barradas. (1991)
51	–100.25	25.77		May 1988–1989	1	Tree block	–	748	–1	Barradas. (1991)
52	–99.14	19.29		Aug, 1988–Aug, 1989	1	Tree block	–	748	–4.6	Barradas. (1991)
53	–99.05	19.34		Jun, 1988–1989	1	Tree block	–	748	–1.9	Barradas. (1991)
54	–99.18	19.38		Sep, 1988–1989	1	Tree block	–	748	–0.9	Barradas. (1991)
55	–99.18	19.42		1961–1963, 1984–1987	54	Tree block	21.64	780	–1.2	Jauregui (1991)
56	–73.6	45.51	Montreal	–	1	–	–	832.85	–2	Oke (1989)
57	11.58	48.15	Munchen	–	2	–	–	1091.98	–2.75	Bru'ndl et al. (1986)
58	118.79	31.78	Nanjing	03, Aug, 2006	100	Tree block, Tree row, Grass	32.68	1100	–1.39	Tang et al. (2009)
59	118.46	32.03		Jul–Sep, 2005	180	Tree block, Tree row	28.53	1033	–0.86	Huang et al. (2008)
60	108.19	22.48	Nanning	8:00–18:00, 10, Jul, 2002	18	Tree row	32.93	1317.79	–1.02	Huang et al. (2007)
61	135.5	34.68	Osaka	17–23, Aug, 1992	15	Tree block	30.88	1395.5	–0.97	Bowler et al. (2010)
62	34.78	30.85	Sde Boqer	Jul, 2007	216	Grass	26.12	530.3	–0.33	Shashua-Bar et al. (2009)
63	112.56	31.22	Shanghai	Jul, 2005	13	Tree block	38.3	1050	–3.74	Zhang and Qin (2008)
64	114.06	22.55	Shenzhen	Nov, 2010	15	Tree block	32	1966.5	–3.77	Zhang et al. (2013)
65	113.97	22.57		21–25, Jul, 2007	168	Tree block	37.26	1924.7	–3.35	Lei et al. (2011)
66	113.97	22.57		Jan–Oct, 2007	12	–	28.08	1933.3	–1.22	Wang and Li (2004)
67	103.77	1.33	Singapore	Jun, 2002–Jun, 2003	2	Tree block	28.8	1933.81	–1.6	Yu et al. (2006)
68	103.82	1.35		09, Jul, 2002	1	Tree block	26.9	2050	4.01	Wong and Yu. (2005)
69	103.76	1.75		Jun, 2003	1	Tree block	26.9	1433.81	–1.5	Yu et al. (2006)
70	18.07	59.34	Stockholm	21–29, Jul, 2004	13	Tree block	19.84	427.98	–0.79	Jansson et al. (2007)
71	121.5	24	Taipei	Jan–Dec, 2003	230	Tree block	–	1215.16	–2.33	Chang et al. (2007)
72	112.53	37.87	Taiyuan	Jul, 2004–Jul, 2005	478	Tree block, Shrub, Grass	31.92	489.97	–2.03	Li et al. (2006a,b) Wang (2005) Li and Liang (2007), Liang and Li (2007), Wu et al. (2008)
73	34.76	32.06	Tel Aviv	Jul–Dec, 1996	17	Tree row	30.08	530	–1.16	Shashua-Bar and Hoffman (2002)
74	34.78	32.08		Jun–Aug	8	Tree block, Tree row	27.1	530	–0.69	Cohen et al. (2012)
75	34.78	32.1		06–07, Jun, 2002	51	Tree block	24.23	747.75	–0.54	Potchter et al. (2006)
76	34.83	32.15		Jul–Aug, 2006	86	Tree row	29.71	530	–1.46	Shashua-Bar and Hoffman (2002)
77	139.43	35.62	Tokyo	Aug, 1994	87	Tree block, Tree row, Grass	29.62	1500	–2.91	Ca et al. (1998)

field observations are essential to unveil such underlying mechanisms.

To obtain a more in-depth understanding of vegetation cooling and warming, in this study we collected 3634 in-situ observations of ΔT_a from the published literature (see Section 2.1, Fig. 1 and Table 1) and normalized the original point-scale of ΔT_a observed at different heights (hereafter termed the normalized variable as ΔT_a^* , see Section 2.1). Subsequently, we conducted a synthetic analysis of ΔT_a^* variations with changes in space-time, climate, vegetation types and canopy phenology stages (see methods). We aimed at the following two objectives: (1) to show how the three commonly acknowledged functions (i.e., background climate forcing, evaporative cooling and canopy shading) contribute to ΔT_a^* ; and (2) to understand how the underlying factors (i.e. background climate variability, vegetation type and growth status, as well as time and location) influence the above three functions to mediate ΔT_a^* .

2. Materials and methods

2.1. Field observation sampling and normalization

To conduct the cross-regional analysis, we collected field measurements of ΔT_a by digitizing from the global published literatures. We selected literature that contains the most basic information, such as vegetation type, observation time, observed height, observed background air temperature (BAT) and observed ΔT_a . The ΔT_a should be the differences between the air temperature of vegetation and of open spaces used as reference. The reference land must be open spaces with non-vegetation. Field measurements were conducted on days with no rain and low wind speed. Based on the above criteria, a total of 3634 samples (Fig. S1) from 77 sites (44 sites with time-series and 33 individual observations) in 35 cities worldwide were collected from the global published literature (Fig. 1, Supplementary dataset). Of the 77 sites, 29 are located in the tropics (0°N–23.5°N), 46 at northern temperate latitudes (23.5°N–50°N), and 2 are situated at northern boreal latitudes (50°N–60°N). None are located in the southern hemisphere. The data collected from the original literature contain mainly the following fields: latitude, longitude, altitude, city, country, year, month, time, UTC time, observed ΔT_a , BAT, vegetation type (see Section 2.4) and vegetation coverage area (S). The information of global in-situ sites are shown in Table 1.

To reduce potential error of ΔT_a caused by the differences in observation height, which vary from 1.0 m to 2.0 m in the published literature, we adopted the following methodologies to normalize the original ΔT_a at different heights to those at 1.5 m: Lee et al. (2011) evaluated the vertical T_a above tree canopy from a subset of forest sites and found that T_a was not sensitive to observation height (< 0.2 °C from 2–15 m above canopy), most likely due to a strong atmospheric mixing which is a universal characteristic of turbulent flow above forests. Here, we assumed that in-situ T_{veg} within forest systems also varies little from 1.0- to 2.0-m observations. Baum (1949) investigated the vertical gradients of mean daytime and nighttime in-situ T_{open} between 0.15 m and 1.5 m throughout a 12-month period (Tables 1 and 2, Baum, 1949). In this case, we simply assumed that T_{open} changes homogeneously from 1.0 m to 2.0 m above open ground and calculated the average vertical

gradient (Table S1). The gradient was applied to convert the original values of T_{open} to a normalized T_{open} at 1.5 m. Subsequently, ΔT_a^* was correspondingly calculated by using T_{veg} minus normalized T_{open} . Because in-situ T_{veg} and T_{open} were observed using the same sensor, we did not consider the potential uncertainty that might have resulted from using different sensors. Furthermore, we took into account the most acknowledged BAT to represent background climate differences, ignoring other microclimate variables such as wind, humidity and vapor pressure deficit, as we chose the records that collected under no-rain and low wind-speed weather.

2.2. Gridded datasets of vegetation and climate variables

Aside from the above in-situ observations, we supplemented vegetation, phenology and climatic variables that were sampled from global gridded products by matching the locations of in-situ sites to gridded imagery, such as Enhanced Vegetation Index (EVI), Normalized Difference Vegetation Index (NDVI), Leaf Area Index (LAI), evapotranspiration (ET), Plant Growth Stage (PGS, see Section 2.4), and downward solar shortwave radiation ($\varnothing$). The data sources of gridded products of EVI, NDVI, LAI, ET, PGS and $\varnothing$ are listed in Table 2. We did not take into account the records before the year 2000 (13% of the total samples) for PGS and vegetation index - related analysis, as MODIS data are only available after 2000.

MODIS ET products (ET_{MODIS}) were estimated using the improved ET algorithm by Mu et al. (2011) instead of the earlier Monteith (1965) method. Also worthy of note is that the spatial resolution of the gridded MODIS EVI, NDVI, LAI, and ET products might be too low for in-situ site matching. To evaluate the potential uncertainty caused by the differences between the footprint of MODIS products and the scale of in-situ observations, we used in-situ climate data to calculate monthly ET ($ET_{in-situ}$) based on the Penman-Monteith equation (Houspanossian et al., 2013) for inter-comparison, which shows satisfactory correlation performances against MODIS EVI, NDVI, LAI, and ET products ($R^2 = 0.33, 0.25, 0.19$ and 0.32 , respectively; $p < 0.001$) (Fig. S2).

2.3. Proxies for three main functions – background climate, evaporative cooling, and canopy shading

Due to the complexity of climatic and vegetative factors in mediating vegetation cooling and warming, for the three main functions – background climate, ET, and shading – we selected the most used proxies, as suggested by former studies.

- BAT as proxy of the background climate effect (Zhang et al., 2013; Zhao et al., 2014; Li et al., 2015);
- $ET_{in-situ}$ as proxy of the vegetation evapotranspiration function (Taha et al., 1991; Bowler et al., 2010; Feyisa et al., 2014; Zhao et al., 2014);
- S as proxy of the canopy shading function (Oke, 1989; Pearlmutter et al., 1999; Dimoudi and Nikolopoulou, 2003).

Table 2

Data sources of gridded products of EVI, NDVI, LAI, ET, PGS, and $\varnothing$.

Name	Products	Version	Spatial resolution	Temporal resolution	References
EVI	MODIS Vegetation Indices (MOD13Q1)	Collection 6	250 m	16-day	Friedl et al. (2002)
NDVI	MODIS Vegetation Indices (MOD13Q1)	Collection 6	250 m	16-day	Myneni et al. (2002) and Friedl et al. (2002)
LAI	MCD15A3H MODIS/Terra + Aqua Leaf Area Index/FPAR (MOD15A3H)	Collection 6	500 m	4-day	Myneni et al. (2002)
ET	Global Terrestrial Evapotranspiration Data Set (MOD16A2)	Collection 5	1 km	8-day	Mu et al. (2011)
PGS	MODIS Global Land Cover Dynamics Product (MCD12Q2)	Collection 6	500 m	8-day	Hufkens et al. (2012)
$\varnothing$	AgMERRA climate forcing datasets	Version 1.1	0.25°	1-day	Ruane et al. (2015)

2.4. Attribution of three main cooling functions to temporal, spatial, vegetative and climatic drivers

Because the background climate, ET and shading functions are closely correlated, we decomposed them into independent underlying variables to gain insight on the drivers controlling ΔT_a^* . The background climate is mainly determined by short-wave radiation, latitude, altitude, season, and time of day. The shading function is principally related to vegetation area, type, vegetation indices (e.g., EVI), and temporal variations (Oke, 1989; Upmanis et al., 1998; Pearlmutter et al., 1999; Dimoudi and Nikolopoulou, 2003; Doick et al., 2014). Moreover, the vegetation evaporative function is related to PGS (Guimberteau et al., 2014), vegetation type (Zhang et al., 2001; Zhou et al., 2015), vegetation indices (e.g., EVI) (Buitenwerf et al., 2015; Wu et al., 2016), and solar radiation (Bi et al., 2015) as illustrated in Fig. S3.

To divide the daytime and nighttime periods, in this study we firstly used the local2Solar function in the solarR package to convert local time to UTC time. The R package solarR includes a set of classes, methods and functions to calculate sun geometry and the solar radiation incident (R Development Core Team, 2012). We further used the sunrise.set function in the StreamMetabolism package, which calculates sunrise and sunset times using MapTools based on the NOAA (National Oceanic and Atmospheric Administration) sunrise sunset calculator, to calculate sunrise and sunset times (Sefick, 2016). Based on this, we lastly distinguished the daytime and nighttime periods for each day. In addition, the in-situ observations were classified into warm (i.e., May-Aug) and cool (i.e., Nov-Dec, Jan-Feb) seasons to illustrate the differences between the two seasonal periods. To present the latitudinal patterns of vegetation cooling, we divided the samples into three broad latitude bands according to the following site locations: 30°S to 30°N (tropics), between 30° and 40° (temperate latitudes) and north of 40°N and south of 40°S (high latitudes). Vegetation was initially classified into three common types: forest, shrub, and grass. Of note, urban forests are mostly developed as defined block parks or striped greenways.

Therefore, in this study forests were further differentiated into tree block and tree row according to their shapes. The trees along boulevards and rivers (e.g., greenways) are classified as tree rows, while those distributed as blocks (e.g., parks) are classified as tree blocks. The shrub reported in a single study (Li and Liang, 2007) was not considered in the analysis. The PGS , which is a proxy of vegetation phenology, was divided into three stages: leaf growth, leaf senescence and dormancy, based on the seasonality of $NDVI$ according to the method of Buitenwerf et al. (2015). The leaf growth stage indicates the period when new leaf onset is more abundant than old leaf drop, whereas the senescence stage is represented by greater old leaf shedding compared to new leaf flushing. The dormancy stage is the period with rare leaf onset and drop.

2.5. Statistical analyses

The bootstrap sampling has been widely used to randomly test the relationship between two dependent/independent variables, especially in meta-analysis studies (Dybala et al., 2019; Guerrero-Ramírez et al., 2019). We used the bootstrapping approach for slope analysis of ΔT_a^* against the proxies of the three main functions – background climate, evaporative cooling, and canopy shading.

The hierarchical partitioning method (Walsh and Mac Nally, 2013) is a technique that involves collinearity to estimate the percentage of explained variance of each predictor variable into independent and joint contribution with all other variables, considering all possible models in a multivariate regression (Chevan and Sutherland, 1991; Pinkert et al., 2017). We used hierarchical partitioning in the hier.part R package to decompose for contribution analysis.

2.5.1. Bootstrapping methods for calculating slope analyses

For each of the above three variables (X), we initially used the bootstrapping method to randomly select a sample (X_i) of observations with replacements from the original X dataset. We then sorted the X vector in ascending order based on the following rules: (1) the

Fig. 2. Temporal, spatial and vegetative variability of mean ΔT_a^* . (a) Diurnal cycle; (b) Seasonal variability; (c) Latitudinal pattern; (d) Vegetation types; (e) PGS stages.

minimum number of X_i is $>25\%$ but $<75\%$ of the total number of X ; and (2) the range of X_i is $>1/4$ of the full range of the sorted vector X . For each bootstrap, we fitted a linear regression model between ΔT_a^* and X_i and calculated the slope of the corresponding linear regression model. For each X_i , 1000 bootstrap replicates were implemented in this calculation.

2.5.2. Hierarchical partitioning for attributing contribution analysis

The hierarchical partitioning method first calculates the goodness-of-fit of models using all combinations of an independent variable. We then followed the method by Walsh and MacNally (2003) to estimate their contributions to the predictor variable. The hierarchical partitioning method implemented in the hier.part R package can compute the contributions of categorical variables and continuous variables to the dependent variable (see details in Walsh and MacNally, 2003). We conducted two processes of contribution analysis related to our two objectives:

- to calculate the contributions of the background climate forcing, evaporative cooling and canopy shading functions (i.e. proxies: BAT, $ET_{in-situ}$ and S variables, respectively) to ΔT_a^* .
- to calculate the contributions of the nine factors mentioned above (latitude, altitude, season, time of day, ϕ , vegetation type, S , EVI, and PGS) to ΔT_a^* , herein termed as C_{lab} , C_{alb} , C_{sea} , C_{tim} , C_{ϕ} , C_{typ} , C_S , C_{EVI} , and C_{PGS} , respectively.

3. Results and discussion

3.1. Urban vegetation cooling and warming effects on local air temperature: temporal, spatial and vegetative variability

The ΔT_a^* from global published literature varied greatly and ranged from -9.7 to 5.2°C (Fig. S1). Overall, 80% of ΔT_a^* observations showed a cooling effect while only 16% demonstrated a warming effect, remaining 4% showing no effect. Given that vegetation cooling and warming are dependent on or related to temporal and spatial factors, as well as vegetation states, we firstly present the general patterns of how

ΔT_a^* varied with changes in time, seasons, latitudes, vegetation types and vegetation growth stages.

3.1.1. Temporal and spatial patterns

The diurnal cycle and seasonality were important temporal factors influencing the variability of vegetation cooling and warming (Fig. 2a and b). Urban vegetation tends to exert stronger cooling effects during the daytime period but reduced cooling and even warming effects during the nighttime period (Fig. S4). This difference between daytime and nighttime periods reached a significant level throughout the year ($p \leq 0.005$, Table S2), except for winter. The strong cooling effects took place in the late morning, between 9:00 a.m. and 12:00 p.m. ($\Delta T_a^* = -1.8 \pm 0.07^\circ\text{C}$), and late afternoon, between 3:00 p.m. and 6:00 p.m. ($\Delta T_a^* = -2.0 \pm 0.07^\circ\text{C}$). It is worth noting that the cooling effect was slightly depressed in the early afternoon between 12:00 p.m. and 3:00 p.m. ($\Delta T_a^* = -1.4 \pm 0.06^\circ\text{C}$) (Fig. 2a). This phenomenon is possibly related to high temperature depression of photosynthesis observed in ecosystems (Taub et al., 2000; Yang et al., 2006), but not exactly consistent with the optimal theory of mid-day stomatal closure (Cowan and Farquhar, 1977). Because ΔT_a^* was not only influenced by evaporative cooling but also by other factors. Besides, several former studies have indeed observed afternoon stomatal closure in different vegetation types (Sayre, 1926; Tenhunen et al., 1982; Correia et al., 1990). Urban vegetation in the warm seasons contributed considerable cooling effects (daytime: $\Delta T_a^* = -1.6 \pm 0.04^\circ\text{C}$; nighttime: $\Delta T_a^* = -0.7 \pm 0.08^\circ\text{C}$) (Fig. 2b); however, no significant cooling effect was observed in the cool seasons, especially during the nighttime period (daytime: $\Delta T_a^* = -0.41 \pm 0.13^\circ\text{C}$; nighttime: $\Delta T_a^* = -0.09 \pm 0.13^\circ\text{C}$).

For spatial patterns, vegetation daytime cooling was related to latitudes, producing a decreasing trend from the tropics ($\Delta T_a^* = -1.5 \pm 0.09^\circ\text{C}$) to the temperate ($\Delta T_a^* = -1.4 \pm 0.04^\circ\text{C}$), and to the high-latitude bands ($\Delta T_a^* = -1.0 \pm 0.09^\circ\text{C}$) (Fig. 2c). Greater differences between warm and cool seasons were observed in the higher latitudes ($>40^\circ\text{N}$: $\Delta T_a^* = -1.4^\circ\text{C}$) and smaller differences in lower latitude zones ($<30^\circ\text{N}$: $\Delta T_a^* = -0.9^\circ\text{C}$) (Fig. S5, Table S3).

Fig. 3. Associations of background air temperature (BAT) of urban areas (BAT), vegetation evapotranspiration calculated from in-situ data ($ET_{in-situ}$) and vegetation area (S) with the normalized gradient (ΔT_a^*) between T_{veg} and T_{open} . (a–c) Box plots of ΔT_a^* in various BAT, $ET_{in-situ}$, S ranges; (d–f) Linear regression slope of BAT, $ET_{in-situ}$, and S against ΔT_a^* , respectively. The line is the fitting curve and the shaded area is the 95% confidence interval.

Fig. 4. Average contributions (C) of BAT, $ET_{in-situ}$, and shading effects to ΔT_a^* .

3.1.2. Vegetative differences

Vegetation types and growth stages influence its cooling and warming effects. The vegetation daytime cooling level differed significantly among tree, shrub and grass lands ($p < 0.001$) (Fig. 2d, Table S4), with tree block ($\Delta T_a^* = -1.7 \pm 0.05^\circ\text{C}$) showing the maximum cooling, followed by tree row ($\Delta T_a^* = -1.3 \pm 0.05^\circ\text{C}$), while grassland generated weaker cooling effect ($\Delta T_a^* = -0.6 \pm 0.08^\circ\text{C}$) compared with forest lands. There were no significant differences in nighttime ΔT_a^* between tree block, tree row and grassland. Vegetation cooling/warming also co-varied with plant PGS (Fig. 2e), with maximum cooling usually during the leaf growth period (daytime: $\Delta T_a^* = -1.7 \pm 0.08^\circ\text{C}$; nighttime: $\Delta T_a^* = -1.5 \pm 0.18^\circ\text{C}$). This temperature mitigation decreased during the leaf senescence stage (daytime: $\Delta T_a^* = -1.4 \pm 0.04^\circ\text{C}$; nighttime: $\Delta T_a^* = -0.4 \pm 0.06^\circ\text{C}$), and reached the minimum during the dormancy stage (daytime: $\Delta T_a^* = -0.1 \pm 0.08^\circ\text{C}$; nighttime: $\Delta T_a^* = 0.4 \pm 0.14^\circ\text{C}$). At the growth ($p = 0.362$) and dormancy ($p = 0.147$) stages, there was no significant difference between daytime and nighttime cooling (Table S5), whereas at the leaf senescence stage vegetation-induced cooling effect was significantly stronger during daytime than during nighttime ($p < 0.001$).

3.2. Associations of background climate, ET and shading functions with ΔT_a^*

Regarding the diverse cooling and warming magnitudes, one of the most pressing issues to be addressed by the scientific community is the thresholds when vegetation performs cooling and warming effects in cities. Fig. 3 shows the box plots of ΔT_a^* in various BAT, $ET_{in-situ}$, S ranges, and the slopes of corresponding simple linear regression models based on the bootstrapping method with 1000 replicates (see Section 2.4).

In general, the background climate plays an important role in determining whether vegetation cools or warms the air temperature. In cooler climate with daily BAT on average $< 10.0^\circ\text{C}$ (Fig. 3a), urban vegetation was associated with a small warming effect ($\Delta T_a^* = 0.4 \pm 0.13^\circ\text{C}$) (69% of the data). Sixty-seven percent of the samples with warming effects were observed during nighttime or during the cool seasons. When daily mean BAT was $> 10.0^\circ\text{C}$, urban vegetation began to exert a cooling effect (average $\Delta T_a^* = -1.7 \pm 0.06^\circ\text{C}$) (Fig. 3a). Slope analysis of the fitting curve between ΔT_a^* and daily mean BAT showed that the vegetation cooling effect becomes more sensitive to BAT increases when BAT was $> 25.7^\circ\text{C}$ (Fig. 3d). The meta-analysis above indicated that it is the BAT variable that mainly determines whether urban vegetation exerts a cooling or warming effect in urban areas, and that the cooling effect of urban vegetation is likely to increase in cities with high BAT. For example, the in-situ air temperature in Shenzhen's urban park in subtropical southern China (latitude: 113.97°N , longitude: 22.57°E) is 5.60°C cooler than in open land during the hot summer season (BAT = 32.3°C) (Lei et al., 2011). Conversely, the magnitude of

Fig. 5. Contributions (C) of BAT, $ET_{in-situ}$, and shading effects to ΔT_a^* along with various BAT ranges.

Fig. 6. Decomposition of the contributions of underlying factors to ΔT_a^* . C_{lab} , C_{alb} , C_{sea} , C_{tim} , C_{ϕ} , C_{typ} , C_S , C_{EVI} , and C_{PGS} are the relative contributions of latitude, altitude, season, time of day, ϕ , vegetation type, S, EVI, and PGS to ΔT_a^* , respectively.

vegetation cooling is always less than 3.0°C in northern Beijing city (latitude: 116.35°N ; longitude: 40.00°E ; BAT = 21.1°C). This trend was also proven by the observations of former studies (Davenport and Hudson, 1967; Shashua-Bar et al., 2010; Chen et al., 2012; Cai et al., 2013), which concluded that background climate was the key influencing factor.

In contrast with the daily mean BAT, to each of the $ET_{in-situ}$ range there always corresponded to a vegetation cooling effect (Fig. 3b). Only a moderate cooling effect was observed when $ET_{in-situ}$ was less. When $ET_{in-situ}$ was > 61.7 mm per month, the vegetation cooling effects started to become much stronger (Fig. 3e), especially when $ET_{in-situ}$ was > 105.0 mm per month ($\Delta T_a^* = -2.4 \pm 0.13^\circ\text{C}$) (Fig. 3b). This finding indicated that the increase of $ET_{in-situ}$ tended to produce a greater cooling effect under higher $ET_{in-situ}$ conditions.

Similar to $ET_{in-situ}$, a moderate cooling effect ($\Delta T_a^* = -0.9 \pm 0.08^\circ\text{C}$) was observed when S was < 30.0 ha. When S became larger ($S > 30$ ha), the vegetation cooling was greatly enhanced, with an average $\Delta T_a^* = -3.3 \pm 0.32^\circ\text{C}$ (Fig. 3c). This more or less coincided with the slope analysis, which revealed a considerable break point of ΔT_a^* against S before and after $S = 35.2$ ha (Fig. 3f).

To better illustrate the performance of vegetation functions in exerting the cooling and warming effects, we chose three most commonly selected proxies (i.e., BAT, $ET_{in-situ}$ and S variables) to represent the background climate, vegetation evaporative function and canopy

shading function, respectively, and attributed their contributions (C_{BAT} , C_{ET} , $C_{shading}$) to ΔT_a^* with different background climates using the hierarchical partitioning method (see Section 2.5). Our results showed that C_{BAT} , C_{ET} and $C_{shading}$, on average, equaled $46.4 \pm 0.10\%$, $40.4 \pm 0.11\%$ and $16.5 \pm 0.13\%$, respectively (Fig. 4). Background climate was modeled as the most important function of vegetation cooling and warming, in comparison with evaporative cooling and canopy shading. Fig. 5 further shows how C_{BAT} , C_{ET} and $C_{shading}$ varied in different BAT ranges. As BAT decreased, $C_{shading}$ dramatically increased, while both C_{BAT} and C_{ET} decreased (Fig. 5). The shading function of vegetation contributed the most in cities with a cooler climate ($BAT < 10.0^\circ\text{C}$, Fig. 5).

These findings provide helpful information to gain a deeper understanding of the relative importance of background climate and vegetation functions in controlling cooling and warming effects.

3.3. Insights on the mechanisms of underlying factor impacts on background climate, evaporative cooling, and shading

To further investigate the underlying factors contributing to urban vegetation cooling and warming, we attributed the three functions (background climate, ET, and shading) to be comprehensively mediated by nine independent underlying factors (latitude, altitude, season, time of day, $\varnothing$, vegetation type, S, EVI, and PGS) (see Section 2.4 and Fig. S3). The contributions of these nine underlying factors to ΔT_a^* were ranked by order of importance as: $C_{PGS} > C_{sea} > C_{lat} > C_{EVI} > C_S > C_{alt} > C_{\varnothing} > C_{DTP} > C_{tim}$ (Fig. 6). The vegetation phenological proxy - PGS ($C_{PGS} = 37.6 \pm 0.11\%$) (i.e., growth, senescence and dormancy), which contributed a large part to evaporative seasonality, acted as the primary biological factor influencing vegetation cooling and warming. Seasonality ($C_{sea} = 23.0 \pm 0.11\%$) and latitude ($C_{lat} = 11.4 \pm 0.07\%$), which controlled background climate, were two other important contributors. The EVI, to some extent representing the mean greenness of plant canopy, and vegetation area controlling shade cooling contributed $9.8 \pm 0.08\%$ and $6.3 \pm 0.06\%$, respectively. The altitude ($C_{alt} = 3.7 \pm 0.03\%$), mean $\varnothing$ ($C_{\varnothing} = 3.5 \pm 0.03\%$), vegetation type ($C_{DTP} = 2.6 \pm 0.04\%$) and time period ($C_{tim} = 2.1 \pm 0.04\%$) played a much less important role.

Previous studies have mainly attributed vegetation cooling and warming to biological factors, such as vegetation indices (Zhang et al., 2013), vegetation types (Feyisa et al., 2014), and vegetation areas (Wong and Yu, 2005; Chang et al., 2007; Cao et al., 2010a,b; Chen et al., 2012). However, by further decomposing the contributions of independent underlying factors to vegetation cooling and warming effects, the vegetation phenological proxy - plant growth stage is modeled in our study as the most important biological contributor. This is probably because vegetation phenology (i.e., leaf onset and litterfall) controls the seasonality of canopy activity, for example, leaf photosynthesis (Wu et al., 2016), plant transpiration (Li et al., 2015; Zipper et al., 2017), as well as canopy cover (Peng et al., 2014) and leaf areas (Zeng et al., 2017) – all of which would considerably impact on vegetation cooling and warming. Especially, under the effects of the urban heat island (UHI), vegetation tends to release more water through transpiration during the leaf growth stage and in turn exerts stronger cooling effects on the local climate (Zipper et al., 2017). The leaf growth stage is expected to be enhanced and extended as a result of extremely extreme high air temperatures (Parece and Campbell, 2018; Walker et al., 2015; Li et al., 2017; Zipper et al., 2016; Jochner and Menzel, 2015). From a more critical standpoint, with the increase of UHI effects, the plant phenology will become increasingly effective in controlling the vegetation cooling and warming. This might in turn undermine the seasonality and latitudinal patterns of vegetation cooling and warming (Lee et al., 2011; Zeng et al., 2017).

4. Conclusions

This analysis of the first global dataset of vegetation cooling and warming effects on urban air temperature indicate that although vegetation generally results in a cooling effect, its direction and magnitude show considerable temporal, spatial and vegetative variations. The background climate, evaporative cooling and canopy shading are three important functions that drive the vegetation cooling and warming. Importantly, this study notes several thresholds: vegetation cooling begin when background air temperature exceeds 10°C ; evaporative cooling increases when evapotranspiration exceeds 62.7 mm per month ; and shading cooling increases sharply when vegetated area exceeds 35.2 ha . The vegetation phenology proxy (i.e., growth stages: leaf growth, leaf senescence and dormancy) ($C_{PGS} = 37.6 \pm 0.11\%$) acts as the primary biotic factor, while seasonality ($C_{sea} = 23.0 \pm 0.11\%$) and latitudes ($C_{lat} = 11.4 \pm 0.07\%$) are two highly important abiotic contributors.

Overall, our findings are important for assessing the effects of vegetation cooling and warming on urban air temperature and providing useful information for future urban greenspace planning aimed at mitigating local warming conditions. To produce maximum vegetation cooling on local climate, it is suggested to plant vegetations with the leaf growth stage coinciding with the warm season periods. This is particularly important for tropical and subtropical regions, where are mainly covered by the evergreen-canopy vegetations with complex canopy phenology. Note also that there might still be some uncertainty caused by observation methodologies, sensors and climatic variability such as wind, humidity, and vapor pressure deficit. More intensive observations are warranted from global in-situ sites using consistent methods.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at [doi:10.1016/j.agrformet.2019.107765](https://doi.org/10.1016/j.agrformet.2019.107765).

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