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GLOBE students, teachers, and scientists demonstrate variable differences between urban and rural leaf phenology

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Abstract

The urban heat island effect, classically associated with high impervious surface area (ISA), low vegetation fractional cover (Fr), and high land surface temperature (LST), has been linked to changing patterns of vegetation phenology, especially spring growth. In this study, a collaboration with the Global Learning and Observations to Benefit the Environment (GLOBE) program, we investigated the effect of the urban environment on the timing of leaf budburst of native deciduous trees in seven cities: Asia (Tokyo, Japan; Bangkok and Korat, Thailand), Europe (Jyväskylä, Finland; Bishkek, Kyrgyzstan), Africa (Dakar, Senegal), and North America (Fairbanks, Alaska). The cities differed not only in population size but also in climate and vegetation type. Using Landsat satellite imagery from each city, we calculated LST, Fr, and ISA, and classified sites within each study area as rural or urban. The timing of leaf flushing, measured by students using GLOBE budburst protocols, was statistically different within all cities, with absolute differences ranging from 1 to 23 days. We assessed the classic urban phenology paradigm, which proposes higher LST, lower Fr, and earlier budburst in urban areas of temperate cities. Of the four temperate cities, Tokyo followed the classic paradigm, but no other city demonstrated consistent support. Urban budburst was advanced in three of the four temperate cities, but in only one of the three tropical cities. Results suggest that while vegetation phenology is consistently different between urban and rural areas, a uniform paradigm based on the explanatory variables in this study did not emerge. Although not testable here, it is likely that alterations to chilling requirements in temperate climates and humidity in tropical climates may also influence observed budburst differences.

Keywords: budbreak, climate change, growing season, heat island, leaf out, seasonality, spring, urbanization

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Introduction

Phenology is the study of the timing of recurring biological cycles (i.e. leaf budbreak, flowering, and leaf fall) and their connection to climate (Richardson *et al*., 2006). The relationship between vegetation phenology and climate indicates dynamic responses of terrestrial ecosystems, generally to climate change, and particularly to springtime increases in temperature (Chmielewski & Rotzer, 2001; Beaubien & Hall-Beyer, 2003; Augspurger, 2004; Chen *et al*., 2005; Piao *et al*., 2006). Climatic controls of vegetation phenology vary strongly geographically and biologically. In high- and mid-latitude temperate ecosystems, leaf flushing is linked to warming spring temperatures (Kramer *et al*., 2000) and

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regional climatic oscillations (D'Odorico *et al.*, 2002; Menzel *et al.*, 2005) while senescence is often a response to photoperiod (White *et al.*, 1997). Drought-deciduous canopies in sub-tropical ecosystems may rapidly senesce during dry season declines in soil moisture and then rapidly flush leaves at the onset of the rainy season (Jolly & Running, 2004; Ishida *et al.*, 2006) while evergreen tropical forests may be less sensitive to moisture variations (Choat *et al.*, 2006). Tropical semideciduous trees usually exhibit interannual variation of leaf flushing before the onset of rains (Do *et al.*, 2005).

Vegetation phenology has a broad impact on Earth system processes, including a large impact on the phase and amplitude of seasonal cycles of atmospheric CO_2 (Keeling *et al.*, 1996; Randerson *et al.*, 1999). Earlier spring growth, which signals the initiation of photosynthetic activity in deciduous canopies, may increase annual CO_2 uptake, although a growing body of evidence suggests a negative feedback from earlier soil moisture depletion (White & Nemani, 2003; Angert *et al.*, 2005). Vegetation phenology also influences mesoscale meteorology (Fitzjarrald *et al.*, 2001; Schwartz & Crawford, 2001), largely through the partitioning of net radiation into sensible and latent fluxes.

Secular climate change associated with well-mixed greenhouse gases has led to generalized trends towards earlier spring throughout much of the northern hemisphere (Menzel & Fabian, 1999; Menzel *et al.*, 2001; Sparks & Menzel, 2002; Schwartz *et al.*, 2006) but localized changes in land use and land cover may also produce extensive alterations to phenological cycles. The urban heat island effect, associated with a high concentration of buildings, roads and other artificial surfaces, may be linked to changing patterns of vegetation phenology, especially spring growth, through a system of feedbacks. First, vegetation is replaced by human-built systems containing extensive coverage of asphalt, concrete, structures, etc., all of which lead to expansions in impervious surface area (ISA) and reductions in vegetation fractional cover (Fr) (Gillies *et al.*, 2003). Second, as permeable surfaces and transpiring vegetation are reduced, the energy balance is shifted towards higher sensible heat flux and lower latent heat flux. Third, air temperatures increase, especially nighttime minimum temperatures (Landsberg, 1981; Adebayo, 1991; Oke *et al.*, 1991), causing vegetation in urbanized areas to begin spring growth earlier than in nearby rural areas (Zhang *et al.*, 2004). We term these processes to be the classic paradigm of phenological response to urbanization. Note that this paradigm is applicable to temperate cities – in tropical cities, the contrast between extant and urban vegetation is more likely to be variable and subject to local irrigation, agriculture, and development patterns influencing moisture regimes.

Observational and remote-sensing evidence exists to support the temperate classic paradigm. Observationally, spring growth was earlier in urbanized areas of 10 temperate cities in northern Europe (Roetzer *et al.*, 2000). In Beijing, urbanization was associated with advances in spring growth, especially since 1978 (Lu *et al.*, 2006; Luo *et al.*, 2007). Urban warming in large cities of eastern North America (Boston, Quebec, Montreal) was linked to herbarium-recorded advances in spring growth (Primack *et al.*, 2004; Lavoie & Lachance, 2006).

Remote-sensing studies also generally support the temperate classic paradigm. Based on data from the Moderate Resolution Imaging Spectroradiometer, the growing season expanded by about 15 days in urban areas of eastern North America (Zhang *et al.*, 2004). Similarly, in eastern United States deciduous broadleaf forests, spring growth in urban areas began about 5.7 days earlier than in surrounding rural areas (White *et al.*, 2002). Remote sensing is a powerful method for tracking vegetation response to urbanization because the posited underlying physical causes (higher ISA and lower Fr) and energy balance effects (higher land surface temperature, LST) may be monitored simultaneously with changes in vegetation phenology, a strategy that is usually impracticable with ground-based studies.

We submit that prior efforts to establish urbanization effects on vegetation phenology are limited: ground-based studies by sparse geographic coverage and variable techniques; remote sensing by coarse spatial resolution – usually 1 km (White *et al.*, 2002; Zhang *et al.*, 2004), potential for atmospheric contamination, and potentially overlapping and/or offsetting phenological responses of multiple species within each pixel. An ideal test of the classic paradigm would therefore be a ground-based dataset of vegetation phenology collected with consistent methods and adequate sampling spanning multiple continents. Before this study, no such data existed. Here, we organized the Global Learning and Observations to Benefit the Environment (GLOBE) Urban Phenology Year (GUPY, http://www.gis.usu.edu/~mikew/Urban_Phenology/Urban_Phenology.v2.html) with the central goal of collecting budburst data in rural and urban areas in seven cities on four continents and the secondary goal of testing whether or not observed phenological differences were related to remotely sensed ISA, Fr, and LST.

Materials and methods

Study area

We collaborated with the GLOBE program [(Butler & MacGregor, 2003), http://www.globe.gov] and recruited GLOBE participation in seven cities in Europe, Asia, Africa, and North America for participation in GUPY (Table 1 and Fig. 1). We also enrolled participating schools from New York, Jordan, and the Philippines but were unable to obtain data reports. The process of city selection was challenging and involved extensive communication among GUPY staff, GLOBE staff and trainers, GLOBE country coordinators, international science education institutions, and individual teachers. While we did not specifically eliminate any locations, we elected to focus our efforts on countries, cities, and schools with a prior record of successful GLOBE participation. Given logistical, communication, and implementation constraints we were unable to standardize GUPY for city population (Fig. 1). The Tokyo agglomeration, for example, has a population of over 33 million while Fairbanks, USA, has a population of only ~30 000. We traveled to all GUPY cities during the winter of 2004/2005 to collaborate with the GLOBE schools, establish measurement locations, and discuss protocol implementation. At each city in the study, we collaborated with a GLOBE city coordinator responsible for overall GUPY implementation. We provided the coordinator and each teacher with a small honorarium following data transmission.

Budburst protocol

Students and teachers followed the standard GLOBE budburst phenology protocol slightly modified for GUPY and translated to the native languages of participating cities. Following is a paraphrased summary

Table 1 Description of GUPY cities (see Fig. 1 for geography and demographics)

City	Sites	Trees	DOY	Fr	ISA	LST	Species	Common name	Landsat
Fairbanks	17	171	120	32	63	20.4	*Betula neoalaskana*	Alaska paper birch	69/15, 27/05/02
Jyväskylä	17	177	124	40	67	21.6	*Betula pendula*	European birch	188/17, 29/05/02
Tokyo	4	32	90	24	62	23.6	*Zelkova serrata*	Japanese zelkova	107/35, 24/09/01
Bishkek	15	150	76	15	79	31.3	*Populus alba*	White poplar	151/30, 08/06/01
Dakar	14	140	100	23	63	30.7	*Adansonia digitata*	Baobob	205/50, 04/11/99 206/50, 11/11/99
Bangkok	5	60	24	13	87	24.3	*Terminalia cattapa*	Tropical almond	129/50, 02/11/00 129/51, 08/01/02
Korat	10	100	35	03	94	27.1	*Acacia harmandiana*	Wattle	128/49, 27/12/99 128/50, 18/02/02

Variables: sites, one site corresponding to one participating GLOBE school; trees, total number of trees measured in each city; DOY, mean budburst day of year; Fr (%), mean fractional cover; ISA (%), mean impervious surface area; LST (°C), mean land surface temperature; Landsat, Landsat 7 ETM+ scene description (path/row and date of acquisition as DD/MM/YY, two scenes for each tropical city).

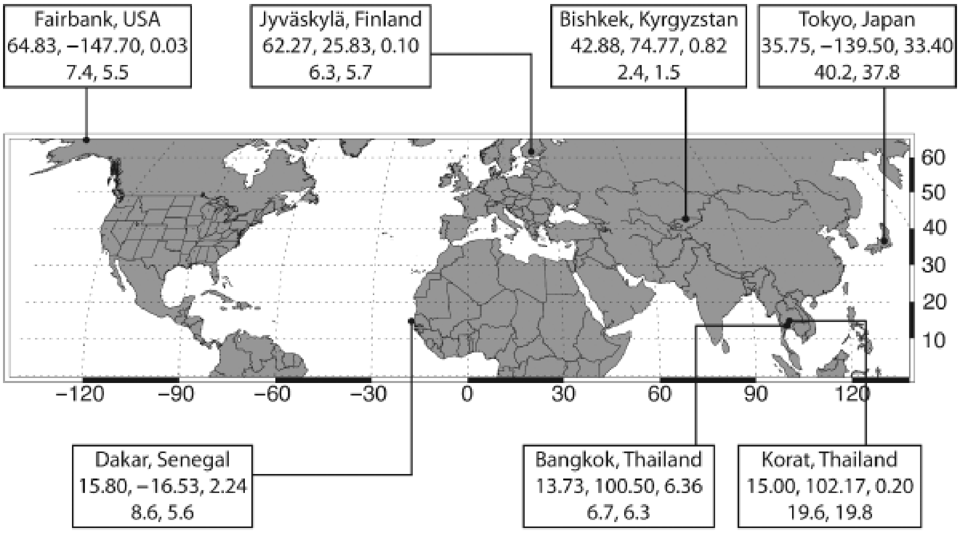

Fig. 1 Location of GUPY cities. Numbers in each legend are as follows: first line, decimal degrees of latitude and longitude (from http://www.getty.edu) and population in millions (from http://www.citypopulation.de); second line, mean and standard deviation of GUPY site distance (km) from the urban core of each city.

(for further details please see the protocols sections of http://www.globe.gov/, click on 'For Teachers', 'Teacher's Guide', 'Protocols').

Site selection. GUPY enrolled between four and seventeen schools per city (Table 1). Students and teachers, in collaboration with GUPY personnel, selected budburst sites with both good proximity to school grounds and trees of the dominant overstory native species. Based on tree species, we categorized sites into two phenological types: (1) temperate deciduous, Finland, USA, Kyrgyzstan, and Japan; and (2) tropical deciduous, Thailand and Senegal. Locations in each city were categorized into rural and urban sites as a component of the ISA analysis.

Tree selection. Once the measurement site was selected, students selected, labeled, and identified approximately 10 trees of one species per school. Students identified tree species before leaf fall to facilitate budburst observation in the spring. Metadata included latitude, longitude, and elevation measured with the GLOBE GPS protocol or with assistance from GUPY staff. Students obtained data for an average of 9.3 trees per school (Table 1). The majority of the trees observed were located along the streets, school campuses, and parks within each city. For a limited number of trees in Bangkok, Fairbanks, and Dakar, reported tree GPS locations indicated data entry errors – in water – and we eliminated these data. Erroneous locations were confined to specific schools; other locations were consistent with known school locations.

Measuring budburst. As budburst is highly variable from year to year, students started monitoring well before the average date of budburst (estimated with assistance from teachers, local naturalists, or GUPY staff). In the spring, 2 weeks or more before the average date of budburst, students began to visit the observation trees about twice a week. Next, after identifying initial stages of bud expansion, students visited the site every day and recorded the date of overall tree budburst (defined in the GLOBE protocols as the detection of '... signs of tiny leaves emerging from inside the bud') when budburst occurred on three branches on the tree. Students recorded one date for each tree and the city coordinators sent summaries to GUPY staff. Note that for each tree, several students typically conducted observation, reducing the chances of anomalous observer bias.

The uncertainty of observer bias or among-observer variability for GLOBE budburst has not been quantified in this or other studies. In GUPY, Dr Gazal and/or Dr Sparrow personally visited every city and conducted intensive trainings with the city coordinator and the individual teachers, who were also usually GLOBE-certified teachers. The training included numerous photographs of the phenological bud development sequence, including budburst, and extensive description of the measurements desired. Dr Gazal also provided follow-up email support. Ultimately, we cannot quantitatively quantify the budburst uncertainty; we assume that the multiple observations at each site, the teacher training, and the 'ensemble' approach of having multiple students observing each tree should provide adequate characterization of site variability in budburst.

Remote sensing

We obtained orthorectified Landsat Enhanced Thematic Mapper Plus (ETM +) data for each city from the Landsat GeoCover database of the Global Land Cover Facility (http://glcf.umiacs.umd.edu/portal/geocover, Table 1) and used ERDAS Imagine (Leica Geosystems, Norcross, GA, USA) to calculate Fr, ISA, and LST. The acquired ETM+ data consisted of imagery in eight spectral bands or channels and was distributed at three different nominal spatial resolutions: one channel of 15 m panchromatic (black and white) imagery (0.52–0.90 μm), six channels of 30 m multispectral imagery within the reflective portion of the electromagnetic spectrum (0.45–2.35 μm), and one channel of 60 m thermal infrared imagery (10.40–12.50 μm).

Ten Landsat images were necessary for coverage of the seven cities with Dakar, Bangkok, and Korat, each requiring two images (Table 1). Images were selected to be representative of growing season conditions for temperate cities (leafed out) and dry season for the tropical cities. Secondary image criteria selected for minimum cloud cover and atmospheric clarity.

For Fr (Gillies *et al.*, 1997, 2003), we first calculated apparent radiance and apparent reflectance using algorithms in the NASA Landsat 7 handbook (Irish, 2000) and then calculated the normalized difference vegetation index (NDVI) as follows:

$$\mathrm{NDVI} = \frac{\rho_2 - \rho_1}{\rho_2 + \rho_1}, \tag{1}$$

where ρ_1 is the apparent reflectance in the ETM + red channel (0.63–0.69 μm) and ρ_2 is the apparent reflectance in the ETM + near-infrared channel (0.76–0.90 μm). NDVI ranges from −1 to 1 with approximate values between 0.1 (bare soil) and 0.8 (dense forest) for land surfaces without snow, cloud, or ice cover. Next, we scaled NDVI between 0 and 1:

$$N^* = \frac{\mathrm{NDVI} - \mathrm{NDVI}_{\min}}{\mathrm{NDVI}_{\max} - \mathrm{NDVI}_{\min}}, \tag{2}$$

where $\mathrm{NDVI}_{\min}$ is the city-specific minimum NDVI, assumed to correspond to 0% vegetation cover, and

$\mathrm{NDVI}_{\max}$ is the city-specific maximum NDVI, assumed to correspond to 100% vegetation cover. Based on visual assessments during site visits, the assumption of 100% vegetation cover for at least some areas with each ETM + scene was justified. Finally, we calculated Fr as

$$\mathrm{Fr} = N^{*2} \tag{3}$$

Note that this method for scaling Fr based on N^* reduces the sensitivity of Fr to atmospheric contamination (Carlson & Ripley, 1997).

We calculated ISA (Gillies *et al.*, 2003) and other remote-sensing metrics with existing methods. First, we conducted an unsupervised classification of land use and land cover for each ETM + image using the ERDAS ISODATA unsupervised classification cluster tool, all six reflective channels, and the following settings: number of clusters 20, initialized from statistics, initializing options principal axis and automatic scaling range, 65 maximum iterations, 0.960 convergence threshold, do not classify zero values, and 1×1 skip factors. We then labeled the resulting cluster files to classes by image interpretation of the source multispectral image and the 15 m spatial resolution panchromatic image. We performed most photointerpretation with the multispectral image displayed in channels 5, 4, and 2 as RGB, although we changed band combinations to discriminate certain features/classes. We assigned each cluster a label that described the closest fit to the target classification (Table 2). As a measure of local spatial heterogeneity, we then extracted land cover classes from a 5×5 pixel window surrounding each tree observation and calculated the city-average Simpson's index of diversity (Simpson, 1949) as follows:

$$\text{index of diversity} = \frac{\sum_{i=1}^{\text{trees}} \left(1 - \left[\sum_{j=1}^{lc} (n/N)^2\right]\right)}{\text{trees}},$$

where trees is the number of trees per city, lc is the number of unique land cover types within the 5×5 neighborhood, n is the number of pixels in land cover j, and N is the total number of pixels in the neighborhood. The index of diversity represents the probability that if two pixels are randomly chosen from the 5×5 neighborhood, they will be different land cover classes. We defined ISA as

$$\mathrm{ISA} = (1 - \mathrm{Fr})_{\mathrm{dev}}, \tag{5}$$

where the subscript, dev, describes those areas classified as anthropogenically developed (Table 2) from the ETM + based land use and land cover mapping (Carlson & Arthur, 2000). We then calculated LST (K) as follows:

$$\mathrm{LST} = \frac{1282.71}{\ln(666.09/L_\lambda + 1)}, \tag{6}$$

where L_λ is the spectral radiance of the thermal infrared band (Markam & Barker, 1986; Irish, 2000). We conducted further calculations in °C.

In a nutshell, we used the remotely sensed data to infer four metrics: (1) how much of the ground surface was covered by green vegetation – Fr, how much of the ground surface in anthropogenically modified areas was covered by impervious surfaces – ISA, the temperature of the land surface – LST, and the variability among land cover classes – index of diversity.

Table 2 Classification system used for land use and land cover mapping with Landsat ETM + imagery

Code	Class type
1	Water
2	Low albedo naturally vegetated and mixed urban features
3	Vegetated features
4	Low density urban and low cover vegetated features
5	Not vegetated and urban features
6	Urban features
7	Cloud, snow, ice, and rock features

We used classes 2, 4, 5, and 6 as urban and other classes as rural and verified site assignments with GUPY city coordinators.

Data analysis

We extracted ETM + derived Fr, ISA, and LST for all pixels containing GUPY budburst observations (ArcMap 9.1, ESRI, Redlands, CA, USA). Note that in some cases, a single 30 m ETM + pixel contained multiple budburst observations. Based on the ETM + imagery and land cover classification (Table 2) used for ISA mapping, we classified all tree observations as either urban or rural. For each city, we calculated mean budburst, Fr, ISA, and LST for the urban and rural sites and tested for statistically significant differences (*t*-test). As a test of the temperate classic paradigm, we first conducted a qualitative test of agreement with presumed differences in remotely sensed variables and budburst and then used a multiple least squares regression analysis to model the relationship between remotely sensed explanatory variables (Fr, ISA, LST) and the budburst response variable (here using all individual tree values). Finally, following results showing that urban vs. rural phenological differences can be related to simple distance from the urban core (Fisher *et al.*, 2006), we estimated the coordinates of the city center from a combination of atlas information and visible and long wave infrared ETM + data, calculated the average location and budburst date of each GUPY site, and for each city assessed the relationship between distance from urban core and measured budburst date.

Ancillary modeling analysis

Preliminary results indicated that in one temperate city, Fairbanks, urban budburst was delayed in comparison to rural budburst – contrary to expectations of urban heat island effects in temperate cities. To explore this finding, we implemented a modeling study based on the first leaf (initial leaf appearance, conceptually similar to budburst) component of the Spring Indices models (Schwartz *et al*., 2006). In the Spring Indices model, as with many phenology models, a chilling summation must be fulfilled in winter before a warm temperature summation leads to spring growth. The original model is based on the response of clonal honeysuckle and lilac to synoptic temperature variations and is largely controlled by three parameters: the temperature below which chilling hours are accumulated, the required summation of chilling hours, and the required thermal summation. Given a timeseries of observations, all parameters may be estimated through optimization techniques. Here, we used an alternate approach to encompass a wide range of parameter uncertainties.

We obtained daily weather records for Eielson Air Force Base (a rural site) and Fairbanks International Airport (an urban site). We used linear interpolation to fill missing values, removed years in which months required for the first leaf simulations (October through mid-August) were missing, and deleted records before a station move at the urban site (1950). The combined records allowed for simulation of first leaf for 1952–1957, 1961–1976, 1980–1986, 1989, 1992–1997, and 2000–2002, a total of 39 years. For each station, we ran the model with the lower chilling threshold set to a range from −1.1 to 10 °C and the chilling summation set to 500–2000 h; a total of 121 parameter combinations were used. For each combination of chilling parameters, we then tuned the thermal summation parameter such that the mean prediction of the last 5 years of the rural site was within 1 day of the GUPY-measured mean budburst date of 120. We then applied the resultant model to the urban site. Thus, for each combination of chilling patterns, an identical model formulation was applied to both rural and urban sites. For each year, we calculated the mean difference in first leaf between the urban and rural sites.

Results

Date of budburst

Mean budburst dates were significantly different between urban and rural sites in all GUPY cities ($P < 0.05$, Fig. 2). In the temperate region, urban budburst was earlier than rural budburst in three of four cities: Tokyo, −11 days; Jyväskylä, −4 days; Bishkek, −2 days. Fairbanks demonstrated the reverse pattern, with budburst 1 day later in urban areas. However, in the tropics, urban budburst was earlier than rural budburst only in Bangkok (−23 days) with Korat and Dakar 9 days later in urban sites (Fig. 2).

Temperate cities differed strongly from tropical cities in cumulative probability distributions of individual tree budburst anomalies (Fig. 3). For temperate cities, >90% of budburst values were ±10 days of the mean. Tropical cities, though, had high probabilities of budburst dates more than 3 weeks outside the mean date (Fig. 3). Bangkok had frequent budburst both earlier and later than the mean; only 40% of dates were ±10 days of the mean. Large Dakar budburst anomalies were skewed toward positive values while Korat budburst was biased towards negative anomalies (not shown). The absolute range in budburst day of year (DOY) also differed between temperate and tropical cities: Fairbanks 12, Jyväskylä 19, Tokyo 18, and Bishkek 26 vs. Dakar 38, Bangkok 48, and Korat 36. No GUPY city coordinators or teachers in tropical cities reported difficulties in observing budburst; consequently, we have no reason to suspect that observational difficulties are responsible for the observed differences in budburst cumulative distributions (Fig. 3).

Remote sensing

Six of seven GUPY cities showed statistically significant differences in LST between urban and rural sites (Fig. 2); differences in Fr occurred in four cities; ISA differed in only one city. Among temperate cities, urban sites in Fairbanks, Jyväskylä and Tokyo had significantly higher LST than rural sites with differences ranging from 1.22 to 4.37 °C while Bishkek had insignificant urban vs. rural LST differences. In the tropics, urban LST exceeded rural LST in Korat and Dakar but in Bangkok, urban areas were cooler (23.92 ± 0.24 °C) than rural sites (25.68 ± 0.29 °C). Similar to temperate LST, urban Fr usually differed from rural Fr: Fairbanks, −21%; Tokyo, −29%; and Bishkek, −3%. Urban and rural sites in Jyväskylä did not significantly differ in Fr with both sites having about 40–43% Fr, the highest Fr value in either temperate or tropical cities. In tropical cities, Fr in both Korat and Bangkok was the lowest among the GUPY cities and showed no significant urban vs. rural differences. Fr differed significantly in Dakar, where urban Fr (17%) was lower than rural Fr (34%). For both temperate and tropical GUPY cities, urban areas tended to have higher ISA than rural sites but only in Fairbanks were the differences between urban and rural sites significant.

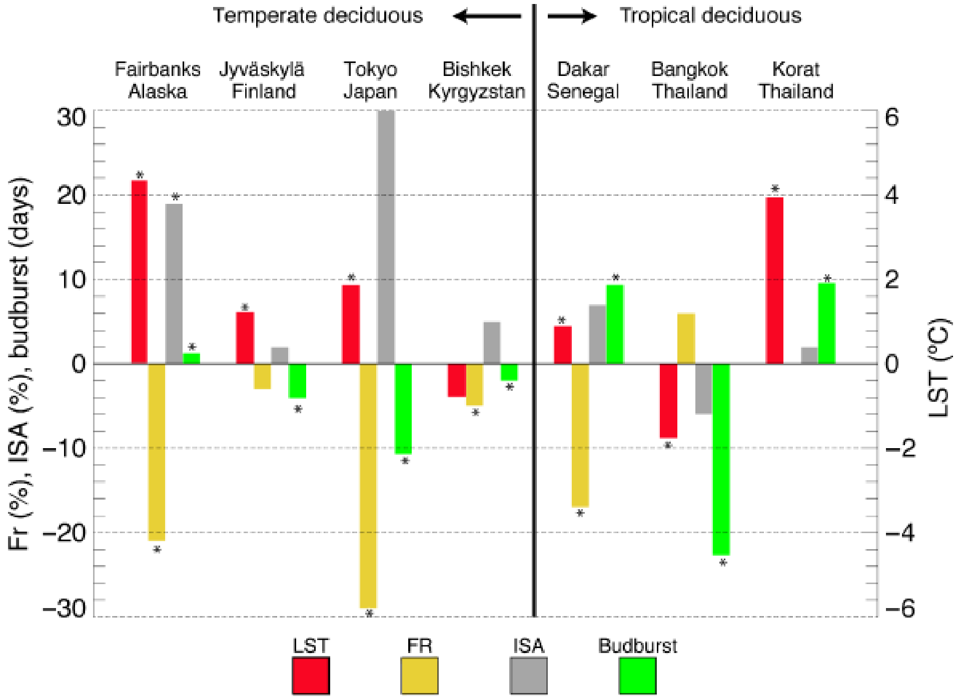

Fig. 2 Mean differences in land surface temperature (LST, secondary *y*-axis), fractional cover (Fr), impervious surface area (ISA), and budburst between urban and rural sites within each city. Values are expressed as urban minus rural; e.g. for Fairbanks, LST was about 4.5 °C higher and budburst was about 1 day later in urban sites than in rural sites. Star over bar indicates statistically significant difference between urban and rural sites (*t*-test, $P<0.05$).

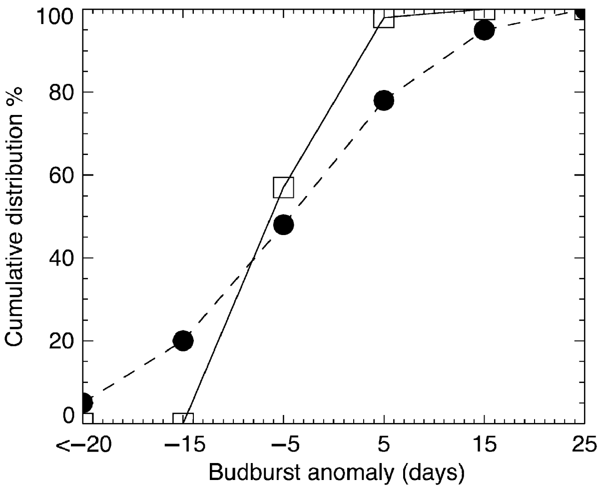

Fig. 3 Cumulative distributions for budburst date anomalies in GUPY cities, averaged by temperate (solid line with squares) and tropical (dashed line with circles) cities. Labels on *x*-axis show bin centers, i.e. 15 includes anomalies ≥ 10 and <20.

Based on the frequency of insignificant differences, we excluded ISA from further analyses.

Mean index of diversity for temperate cities was Fairbanks 0.52, Jyväskylä 0.60, Tokyo 0.53, and Bishkek 0.60; and in tropical cities: Dakar 0.46, Bangkok 0.58, and Korat 0.48. Statistically significant differences in index of diversity existed among cities (Kruskal–Wallace *H*-test $P<0.001$). Assessed across climate zones, index of diversity was significantly different (*t*-test, $P<0.001$): 0.56 in temperate cities vs. 0.49 in tropical cities.

Testing the classic paradigm

The GUPY findings suggest that while budburst differed significantly between urban and rural areas in all cities (Fig. 2), only limited evidence exists to support the classic paradigm. Assessed qualitatively (Table 3), only one temperate city, Tokyo, fully followed the pattern of higher LST, lower Fr, and earlier budburst expected in urban areas for the temperate classic paradigm. Jyväskylä and Bishkek showed partial agreement with higher LST and earlier budburst but no significant difference in Fr. Fairbanks showed LST and Fr differences consistent with the classic paradigm but budburst changes were opposite. As expected, no tropical GUPY cities supported the classic paradigm. Tropical cities also differed within the biome: Dakar and Korat were similar in LST and budburst while Bangkok showed opposite responses (Fig. 2 and Table 3).

Table 3 Qualitative assessment of the temperate classic paradigm of urbanization effects on budburst

	LST higher in urban sites	Fr lower in urban sites	Budburst earlier in urban sites	Evidence supports classic paradigm
Fairbanks	Yes	Yes	No	No
Jyväskylä	Yes	nd	Yes	Partially
Tokyo	Yes	Yes	Yes	Yes
Bishkek	nd	Yes	Yes	Partially
Dakar	Yes	Yes	No	No
Bangkok	No	nd	Yes	No
Korat	Yes	nd	No	No

Yes (No) indicates a significant difference (*t*-test, $P<0.05$) in agreement (disagreement) with column heading. Fr (%), fractional cover; LST (°C), land surface temperature; nd, no significant difference.

Multiple regression models derived from individual tree observations within each city produced statistically significant equations for four cities, but again only Tokyo followed the temperate classic paradigm with a positive slope between Fr and budburst ($r^2 = 0.41$; $P<0.0001$, Table 4, Fig. 4) and a negative slope between LST and budburst ($r^2 = 0.19$; $P<0.0001$). As per the classic paradigm, trees in urban sites with lower Fr and higher LST had earlier budburst date than trees in rural sites (Fig. 4). While no other temperate cities exhibited significant models between LST, Fr, and budburst, models were significant for all tropical cities. All tropical models showed positive slope coefficients for LST, showing that increased surface temperatures delayed budburst. Dakar had a similarly contravening sign for Fr but Bangkok and Korat had later budburst associated with higher Fr, as for Tokyo (Table 4).

Distance from urban core

For all temperate cities, the slope between distance from urban core and measured budburst date was positive (Fairbanks 0.08, one outlier removed; Jyväskylä 0.37; Tokyo 0.14; Bishkek 1.05), supporting remotely sensed results for Providence, Rhode Island (Fisher *et al*., 2006). However, the slope variable was statistically significant at the 5% level only for Jyväskylä. Our data did not support a power (Fisher *et al*., 2006) or exponential (Zhang *et al*., 2004) fit between distance and budburst. For tropical cities, the pattern was reversed, with all slope variables being negative (Dakar, −0.82; Bangkok, −1.04; Korat, −0.21) and the relationship statistically significant at Dakar and Korat.

Table 4 Multiple regression analysis with budburst day of year (DOY) as the response variable and land surface temperature (LST, °C) and fractional vegetation cover (Fr, %) as explanatory variables

City	Intercept	LST	Fr	r^2
Tokyo	98.25 (<0.01)	−0.49 (0.43)	14.86 (<0.01)	0.42
Dakar	91.19 (<0.01)	0.37 (0.50)	−13.32 (<0.01)	0.11
Bangkok	−125.08 (<0.01)	6.13 (<0.01)	4.60 (0.79)	0.34
Korat	0.00 (1.00)	1.23 (<0.01)	42.85 (0.19)	0.10

Results shown only for cities with statistically significant regressions (*F*-test, $P<0.05$). Values in parentheses are *P*-values for regression coefficients.

First leaf modeling

Simulations of first leaf for urban and rural stations in Fairbanks showed temporally variable differences between the urban and rural sites (Fig. 5). Through about 1970, differences were usually close to zero. Then, at the same time as the commencement of rapid population growth in Fairbanks in the 1970s (Magee *et al*., 1999), urban budburst was consistently earlier than rural budburst, often by 2–4 days (Fig. 5). In the early 1990s, differences became progressively less negative and then generally switched to the reverse pattern of an urban delay in first leaf by the mid-1990s.

Discussion

The overall response of vegetation phenology to climate change is indicative of a secular response towards earlier spring associated with warming trends, especially over multi-decadal time frames and in the northern hemisphere (Schwartz *et al*., 2006) and specifically in regions of North America (Cayan *et al*., 2001; Beaubien & Hall-Beyer, 2003), Europe (Hanninen, 1995; Kramer *et al*., 2000; Chmielewski & Rotzer, 2001; Chmielewski *et al*., 2004; Picard *et al*., 2005; Menzel *et al*., 2006), and Asia (Matsumoto *et al*., 2003; Yu *et al*., 2003; Chen *et al*., 2005; Piao *et al*., 2006). Increasingly, phenological changes are associated with anthropogenic activities (Root *et al*., 2005). Our study suggests that urbanization impacts on phenology are associated with at least three important features that may be distinct from secular warming impacts.

First and most centrally, our study suggests that while urbanization is consistently associated with statistically significant differences in budburst between urban and rural areas, vegetation responses are individualistic and often contrary to patterns found in the secular global warming signal or in the temperate classic paradigm of urbanization. Three of seven cities experienced delays in budburst.

Second, in Fairbanks, as for satellite findings in cold regions of the conterminous United States (White *et al.*, 2002), we found an urban delay in spring phenology. With a pronounced urban heat island effect (Magee *et al.*, 1999) with peak warming at night and during the cold season, why would urban budburst be delayed? For boreal latitude trees, warming during fall increases chilling requirements and may lead to delays in subsequent spring budburst – a paradoxical effect of climate change on boreal tree phenology may, thus, include offsetting effects leading to minor changes or even delays in spring phenology (Heide, 2003). GUPY data and our simulations of first leaf in Fairbanks (Fig. 5) showing urban delays in phenology beginning in the late 1990s are consistent with the provocative claims in Heide (2003).

Third, GUPY tropical cities and species studied do not – in contrast to other locations (Jolly & Running, 2004) – support a conceptual model of phenological responses to precipitation or soil moisture conditions. Principally, tropical budburst DOY in Thailand (Bangkok 24, Korat 35) and Dakar (100) occur during the peak of the dry season, indicating that increases in bulk soil moisture are unlikely to be responsible for leaf flushing. Working with a semideciduous Sahelian species, Do *et al.* (2005) also found that interannual variability in leaf flushing was unrelated to the timing of precipitation or shifts in soil moisture. Flushing was, however, highly related to decreases in vapor pressure deficit

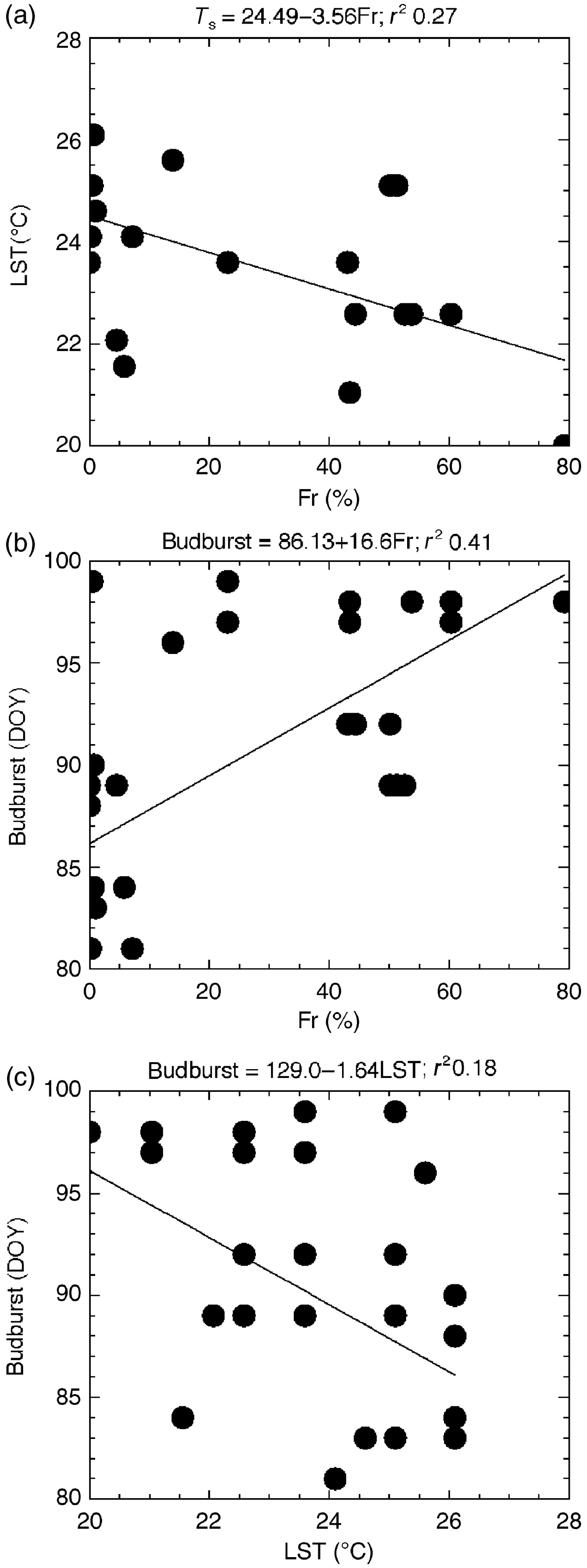

Fig. 4 Regression analysis for *Zelkova serrata* in Tokyo, Japan, in spring 2005: (a) fractional vegetation cover (Fr) and land surface temperature (LST), (b) Fr and budburst day of year (DOY), (c) LST and budburst.

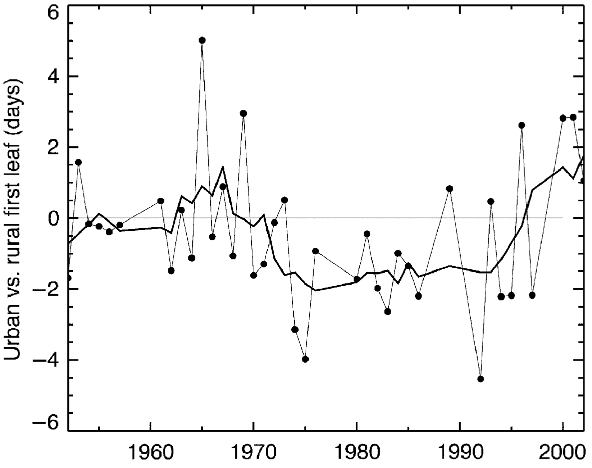

Fig. 5 Differences in simulated first leaf between an urban (International Airport) and rural (Eielson Air Force Base) site in Fairbanks, Alaska. Points and thin line show individual years (see text for list of missing years); thick line shows five-point running average. Values below the horizontal line show a prediction of earlier spring in urban areas.

(VPD). Although highly speculative, GUPY data support a VPD connection (Fig. 2). Based on the known positive relationship between LST, the saturation vapor pressure at LST, and VPD (Hashimoto *et al.*, 2007) and observed differences in GUPY LST and budburst, the following process may influence observed tropical budburst differences: higher (lower) LST indicates higher (lower) VPD and, as per Do *et al.* (2005), higher (lower) VPD leads to delays (advances) in budburst. In GUPY tropical cities, observed budburst differences are consistent with the VPD interpretation, leading to budburst delays in Dakar and Korat and advances in Bangkok. While we cannot provide a definitive explanation for the posited urban vs. rural differences in VPD, cumulative probability distributions for tropical cities (Fig. 3) support a contention that spatial variability in water bodies, irrigation, and/or local land use and land cover (Arthur-Hartranft *et al.*, 2003) may be associated with localized VPD differences.

While the assessment of budburst date vs. distance from urban core was statistically insignificant for most temperate cities, the results are at least qualitatively consistent with concepts found in other work (Fisher *et al.*, 2006) showing that geographic distance may be a good predictor of budburst changes associated with urbanization. We suspect – although we cannot currently prove – that a more intensive ground-based sampling campaign would show more consistently significant results. As with other results, tropical cities showed patterns opposite to the temperate classic paradigm, further cementing the inapplicability of temperate conceptual models of phenology to tropical biomes.

We found that remotely sensed LST, Fr, and ISA could not be used consistently to explain observed differences in urban vs. rural phenology (Fig. 2, Table 3) and that in cases where statistically significant models existed, r^2 was low and the model formulation was inconsistent (Table 4). Technical and logistical factors may have influenced these findings.

Five technical issues exist. First, the spatial resolution of the Landsat sensor may have been inadequate to represent Fr (30 m), LST (60 m), and land cover (index of diversity values indicated a 50% probability of obtaining a different land cover in the sampled 5×5 grid) for the GUPY trees. For GUPY cities, index of diversity values suggest that land cover classifications may have higher uncertainties in temperate than in tropical cities. Second, the LST is radiometric temperature, not air temperature. While detailed research suggests that the LST and air temperature are strongly related (Ben-Dor *et al.*, 2001), particularly over highly vegetated surfaces, local atmospheric conditions, especially high humidity, can introduce divergences. Third, although numerous studies use single-date acquisitions to characterize the urban environment (Stathopoulou & Cartalis, 2007; Yue *et al.*, 2007), the seasonal timing of Landsat acquisition may not have captured the urban gradient at the time of year most relevant for phenological activity. Due to data availability, a consistent set of images spaced evenly throughout the year for all cities was not possible. The problem was worst for tropical cities, where often only one or two cloud-free images are available per year. Fourth, it is possible that the LST, Fr, and ISA may have changed between Landsat imagery (Table 1) and GUPY data collection during 2005. Fifth, it is possible that localized microclimates (Fisher *et al.*, 2006) and vegetation conditions not represented in the remotely sensed data may have limited our ability to provide consistent explanations for the measured budburst differences.

Logistically, the strictures of a volunteer-based campaign introduced some problems. For temperate cities, the variable geographic sampling within GUPY may have influenced inconsistent findings; Tokyo, which followed the classic model, also had the most widely dispersed schools (Fig. 1). It is possible that if a similar distance-based gradient were available in other cities, more data would support the temperate classic paradigm. Similarly, because most observations were made at or near school grounds, it is likely that even the rural schools contain some urbanization signature and that a rigorously controlled transect-based campaign might have found different urban vs. rural differences.

The GUPY was an ambitious and challenging project that both benefited and suffered from the volunteer nature of the GLOBE program. Given the technical and logistical challenges discussed previously, we recommend that future work might wish to focus on a paired study of temperate cities of approximately the same size and containing at least the same genus, but located in cold and warm climates. High-resolution satellite imagery or multisensor approaches (Sawaya *et al.*, 2003; Rodemaker *et al.*, 2004; Greenberg *et al.*, 2006) in the four seasons would be extremely beneficial. Ground sampling should be organized along a previously defined gradient of Fr and LST and may benefit from recent advances in measurement technology (Richardson *et al.*, 2007).

Conclusions

In summary, the GUPY project illustrates two main concepts. First, the GLOBE program can be an effective vehicle with which to address short-term question-based research that would otherwise be impracticable to attempt through traditional funding mechanisms. GLOBE's worldwide reach, extensive scientific contacts, and governmental agreements greatly facilitated GUPY logistics, which, though formidable, were tractable.

Similarly themed research projects could be proposed to existing GLOBE staff (www.globe.gov). Second, using the GUPY's consistent methods and extensive range across multiple continents, we demonstrated that with one exception (Tokyo), the classic paradigm of urbanization effects of leaf phenology is not fully supported in temperate cities. Cold climate and high latitude appear to reduce the effects of the urban heat island on plant phenology, likely through a feedback on chilling requirements. As expected, the temperate classic paradigm was universally unsupported in the tropical cities studied, where phenological responses to urbanization are varied and may be related to localized atmospheric conditions, not regional temperature or precipitation condition. Urbanization studies within the context of global change biology may, therefore, wish to more individually assess phenological variability, especially outside of moist temperate biomes.

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