1 **Remotely sensed assessment of urbanization effects on**
2 **vegetation phenology in China's 32 major cities**

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18 **Abstract:**

19 Urbanization-induced phenological shifts may provide evidence on how vegetation
20 will respond to global warming. However, the effects of urbanization on vegetation
21 phenology are poorly understood in urban environments. Using MODIS data between
22 2007 and 2013, we investigated the trends of the phenological metrics (i.e., start, end,
23 and length of growing season: SOS, EOS and GSL) of individual cities and across
24 cities relative to rural areas for China's 32 major cities. We found that the effects of
25 urbanization on phenology decayed exponentially toward rural areas, and were
26 closely related to the land surface temperature (LST) for more than half of the cities.
27 The phenological sensitivity to temperature were 9-11 days SOS advance and 6-10
28 days EOS delay per 1°C increase of LST. On average across all cities, the growing
29 season started 11.9 days earlier and ended 5.4 days later in urban zones compared to
30 rural counterparts. The urbanization effects increased with increasing latitudes,
31 following the pattern of urban heat island effects in general. Our study suggests the
32 value of urban environments in studying the phenological responses to future global
33 change. However, the urbanization impacts are complex and need more direct
34 observations, experimental manipulations, and cross-boundary inter-comparison
35 studies.

36 **Keywords:** start of growing season; end of growing season; urban heat island;
37 vegetation phenology; global warming; urbanization

38 **1 Introduction**

39 Change in vegetation phenology not only is a highly sensitive indicator of the effects
40 of climate change but also can regulate climate by altering the energy, water, and
41 carbon exchanges between land surface and the atmosphere (Baldocchi et al., 2001;
42 Zhang et al., 2006; Piao et al., 2008; Richardson et al., 2010; Richardson et al., 2013;
43 Keenan et al., 2014). Numerous studies suggested that the vegetation phenology in the
44 northern mid- to high-latitudes has been greatly altered by global warming,
45 characterized by an earlier start and longer duration of growing season associated with
46 increasing temperature (e.g., Piao et al., 2006; Delbart et al., 2008; Aono et al., 2008;
47 White et al., 2009; Zeng et al., 2011; Jeong et al., 2011; Dragoni et al., 2012; Cong et
48 al., 2012; Keenan et al., 2014). However, both the magnitude, pattern, and
49 mechanisms of the warming effects remain uncertain because of lacking long-term
50 observations and the difficulties in manipulating field temperature for natural
51 vegetation experimentally (Zeng et al., 2011; Cong et al., 2012; Jochner et al., 2013;
52 Garonna et al., 2014).

53

54 Urban areas tend to have higher temperatures than the surroundings, referred to as
55 urban heat island (UHI), largely resulted from the rise of impervious surface at the
56 expense of vegetated and evaporating soil surfaces that reduces latent heat flux and

57 increases sensible heat flux (Oke, 1982; Arnfield, 2003; Clinton and Gong, 2013).
58 Cities with apparent UHI effects may provide a useful, unintended laboratory to
59 assess how vegetation will respond to a global warming (White et al., 2002; Ziska et
60 al., 2003; Zhang et al., 2004; Neil and Wu, 2006; Luo et al., 2007; Mimet et al., 2009;
61 Jochner et al., 2013). For example, Zhang et al. (2004) reported that the phenological
62 differences between urban and rural areas related linearly and significantly ($p <$
63 0.0001) to the temperature differences in the eastern North America, with 3 days
64 advance of vegetation greenup for each 1°C increase in temperature. The phenological
65 shifts in urban areas can affect many ecological processes including net primary
66 production (Imhoff et al., 2004) and seed set (Santandreu and Lloret, 1999).
67 Phenological shifts may create an asynchronous mismatch between pollinators and
68 their flowers (Kudo et al., 2004). In addition, prolonged GSL may affect human health
69 by lengthening the allergy seasons and thus increasing the severity of allergies (Van
70 Vliet et al., 2002; Cecchi et al., 2010). An accurate knowledge of the urbanization
71 effect on phenology, therefore, can not only help enhance understanding the
72 phenological responses to warming but also be essential for formulating mitigation
73 strategies in cities.

74

75 At present, the effects of urbanization on vegetation phenology are poorly understood
76 (Jochner et al., 2012, 2013). First, whether there exists an urbanization effect remains

77 inconclusive. Several studies observed advances of the start of growing season (SOS)
78 and delays of the end of growing season (EOS) in urban areas relative to rural
79 counterparts by field measurements (Roetzer et al., 2000; Lu et al., 2006) or
80 remote-sensing analyses (White et al., 2002; Zhang et al., 2004), whereas others
81 demonstrated an insignificant change and even a delay of the SOS in urbanized areas
82 for some cities (Gazal et al., 2008; Jochner et al., 2012, 2013). Second, the
83 relationship between UHI and vegetation phenology is controversial. Zhang et al.
84 (2004) indicated that the UHI intensities (urban-rural temperature differences) were
85 significantly correlated with urban-rural phenological differences across cities, while
86 other observations showed that UHI effects could not explain the urban-rural
87 phenological differences for many cities especially in the tropical regions (Gazal et al.,
88 2008) or for many species (Jochner et al., 2013). Third, the background climate was
89 identified as one major driver for the large-scale spatial variability of vegetation
90 activity (Piao et al., 2003), UHI intensity (Zhou et al., 2014b; Zhao et al., 2014), and
91 the warming effect on vegetation (Cong et al., 2012), but its relationship with the
92 phenological changes in urban areas is unclear. With accelerating urbanization (Angel
93 et al., 2011; Seto et al., 2012; United Nations, 2014) and warming trend (IPCC, 2013)
94 worldwide, there is a strong impetus to better understand the phenological shifts
95 associated with urbanization over large areas.

96

97 As the world's most populous country, China experienced the rapidest urbanization in
98 past decades in the world and the trend is expected to continue in upcoming decades
99 (Seto et al., 2011, 2012; United Nations, 2014). Meanwhile, China covers a wide
100 temperature gradient decreasing from south to north and a large precipitation gradient
101 decreasing from southeast to northwest. Thus, China is ideal to examine the
102 urbanization effect at a regional level. In this study, we analyzed the effect of
103 urbanization on vegetation phenology in 32 major cities distributed across China
104 using Moderate Resolution Imaging Spectroradiometer (MODIS) data in conjunction
105 with cloud-free Landsat Thematic Mapper (TM) and Enhanced Thematic Mapper Plus
106 (ETM+) images between 2007 and 2013. Our main objectives were to investigate (1)
107 the trend of the urbanization effect on phenology of individual cities, (2) the spatial
108 variability of the urbanization effects on phenology across cities, and (3) their
109 relationship with UHI effects and background climate in China.

110

111 **2 Data and methods**

112 **2.1 Remotely sensed vegetation phenology**

113 Our study covered China's 32 major cities. They are municipalities or provincial
114 capitals (mostly the largest city in the municipality or province) except Shenzhen,
115 which is China's first special economic zone established in 1978 and is now
116 considered as one of the global fastest growing cities (Fig. 1). Most cities are

117 surrounded mainly by cultivated land, and the rest by forests (e.g., Hangzhou and
118 Fuzhou) or grassland (Lhasa). Land cover maps within the administrative boundary of
119 each city for the year 2010 were derived from the cloud-free Landsat TM/ETM+
120 images with a moderate spatial resolution of 30 m. The land covers were classified
121 into four broad types (i.e., cropland, urban land, water body, and other land cover)
122 using the maximum likelihood classification approach (Zhao et al., 2015). The
123 accuracies of the classified products were assessed by using the high-resolution
124 images and pictures incorporated in Google Earth Pro® (GE). The accuracies,
125 measured by Kappa coefficients, were generally larger than 0.80 for all those cities.
126 Further details on land cover data can be found in our previous work (Zhao et al.,
127 2015). To investigate the geographic variations of the urbanization effect on
128 phenology, these cities were grouped into six geographic regions: North China
129 (Beijing, Hohhot, Shijiazhuang, Taiyuan, and Tianjin), Northeast China (Changchun,
130 Harbin, and Shenyang), East China (Fuzhou, Hangzhou, Hefei, Jinan, Nanchang,
131 Nanjing, and Shanghai), Central-south China (Changsha, Guangzhou, Haikou,
132 Nanning, Shenzhen, Wuhan, and Zhengzhou), Southwest China (Chengdu,
133 Chongqing, Guiyang, Kunming, and Lhasa), and Northwest China (Lanzhou, Urumqi,
134 Xi'an, Xining, and Yinchuan) (Fig. 1). The east, central-south, and southwest parts of
135 China have typical humid-hot climate. Northeast China, North China, and Northwest
136 China have typical humid cold, semi-humid/arid temperate, and arid climates,
137 respectively.

138

139 The version-5 Aqua MODIS enhanced vegetation index (EVI, 16-day composite) with
140 a spatial resolution of 250 m (MYD13Q1) was used to extract phenology information
141 for the period 2007-2013. Compared with the most widely used normalized difference
142 vegetation index (NDVI) (e.g., Piao et al., 2006; White et al., 2009; Zeng et al., 2011;
143 Jeong et al., 2011; Keenan et al., 2014), the EVI minimizes the impacts of canopy
144 background variations while retaining the sensitivity to small changes in vegetation
145 activities (Dallimer et al., 2011), and its accuracy has been assessed over a widely
146 range of locations and time periods (Huete et al., 2002). The EVI was believed to be
147 more appropriate for monitoring vegetation dynamics in urban areas usually covered
148 by sparse vegetation (Zhang et al., 2004; Dallimer et al., 2011; Zhou et al., 2014a).
149 The Aqua instead of Terra MODIS EVI datasets were used in order to keep
150 accordance with the Aqua MODIS land surface temperature (LST) products used in
151 this study, which were believed to be more representative for characterizing the UHI
152 effects and thus being widely used in UHI studies (e.g., Peng et al., 2012; Clinton and
153 Gong, 2013; Zhou et al., 2014b).

154

155 We focused on three phenological metrics in this analysis: SOS, EOS, and growing
156 season length (GSL), and the TIMESAT algorithms (Jönsson and Eklundh, 2004;

157 Chen et al., 2004) were used to calculate these metrics based on EVI time series.
158 Three methods were available in the TIMESAT software: adaptive Savitzky–Golay
159 filtering, asymmetric Gaussian, and double logistic. Both asymmetric Gaussian and
160 double logistic approaches use semi-local methods and can make good predictions of
161 the SOS and EOS, especially for noisy time-series (Hird and McDermid, 2009). We
162 applied the double logistic function since it performs better for data smoothing in high
163 latitudes than the asymmetric Gaussian approach (Zeng et al., 2011).

164

165 Two methods were available to determine the dates of the SOS and EOS from EVI
166 time series in TIMESAT software: a) start and end where fitted curve reaches a
167 threshold value, and b) start and end where the fitted curve reaches a proportion of the
168 seasonal amplitude measured from the left and right minimum values, respectively.
169 The second method was utilized in this study because the EVI values in urban areas
170 were usually much lower than that in buffer areas (Zhou et al., 2014a), which make it
171 difficult to find a threshold value to determine the SOS and EOS dates. We defined
172 the SOS and EOS as 20% of the seasonal amplitude measured from the left and right
173 minimum levels, respectively (Fig. 2). The proportion was selected based on the
174 previous experiences (Eklundh and Jonsson, 2009; White et al., 2009; Brown et al.,
175 2010; Cong et al., 2012; Buyantuyeva and Wu, 2012). The GSL was then estimated as
176 the date differences between EOS and SOS.

177

178 We calculated the SOS, EOS, and GSL for each year separately during the period
179 2007-2013. Due to the complexity of urban surface, there were outliers for the
180 phenological estimates. To reduce those uncertainties, pixels with the SOS earlier than
181 the 50th day of year or later than the 180th day of year were excluded for the SOS
182 analysis. The threshold values were loosely determined according to previous
183 practices (White et al., 2009; Cong et al., 2012). Similarly, the EOS was constrained
184 between the 240th and 330th day of year (Zhang et al., 2006). Following general
185 practices in previous studies, we did not attempt to validate the remotely-sensed
186 phenological metrics with field observations due to definition difference (i.e.,
187 ecosystem vs. species) and varying uncertainty sources (Rodriguez-Galiano et al.,
188 2015). Nevertheless, our approach for calculating phenological metrics is widely used
189 in similar studies (e.g., Zeng et al., 2011; Cong et al., 2012) which has shown good
190 agreement with ground observations in Europe (Rodriguez-Galiano et al., 2015).

191

192 **2.2 Identifying urbanization effect on phenology**

193 We hypothesized that the effect of urbanization on phenology is strongest in urban
194 centers and decreases gradually towards rural areas (e.g., Zhang et al., 2004). To
195 demonstrate this effect, it is necessary to define and delineate urban and surrounding

196 buffer areas on maps. The urban area was defined by three steps (Zhou et al., 2014b):
197 1) a built-up intensity (BI) map was generated from each urban coverage map using a
198 1 km × 1 km moving window method; 2) a 50% threshold of BI was used as a
199 criterion to separate the BI maps into high- and low-intensity built-up land; and 3) the
200 high-intensity built-up polygons were aggregated to delineate the urban border with
201 an aggregation distance of 2 km, which is sufficient to include the scattered and most
202 adjacent high-intensity built-up patches into the urban class. The urban areas ranged
203 from 47.6 km² (Lhasa) to as much as 2350.6 km² (Tianjin) in the year 2010.

204

205 A series of buffers extending 0–1, 1–2, 2–5, 5–10, 10–15, 15–20, and 20–25 km from
206 the urban edge outward were then created for all the 32 cities individually (Fig. 3A).
207 In order to quantify the effect of urbanization on phenology, it is necessary to define
208 the rural phenology (referring to the baseline or reference phenology) for each city.
209 We defined the phenology in the farthest buffer (20–25 km) as rural or baseline
210 reference. This definition should be able to reflect the background phenology because
211 the mean footprint of urban areas on phenology had been estimated to be less than 20
212 km away from urban perimeter in eastern North America (Zhang et al., 2004) and
213 China (Zhou et al., 2015). Pixels that were water body or with elevation more than 50
214 m higher than the highest point in the urban area were excluded from this analysis
215 because these pixels may overshadow the urbanization effects on phenology (e.g.,

216 White et al., 2002; Zhou et al., 2014a). Digital Elevation Model (DEM) at a 3
217 arc-second (approximately 90 m) spatial resolution from the Space Shuttle Radar and
218 Topography Mission (SRTM) (downloaded from <http://earthexplorer.usgs.gov/>) was
219 used to exclude altitude effects.

220

221 We generated urban and buffer areas for each city in 2010 and assumed that the urban
222 area and buffers delineated in 2010 can be used to represent those in 2007-2013. We
223 did not remove cropland from this analysis as some previous efforts did (e.g., Zhang
224 et al., 2004; Buyantuyeva and Wu, 2012) for two main reasons. First, urbanization
225 mainly occurred in agricultural land of China (Liu et al., 2005) and the resultant
226 changes of phenology represent one essential part of the urbanization effect on
227 vegetation. Second, the number of vegetated, non-agricultural pixels was too small for
228 some cities to conduct reliable statistical analysis. For example, less than 10 EVI
229 pixels were left after we removed the classified cropland in the 0-1 km and 1-2 km
230 buffers in Xi'an, Shijiazhuang, and Hefei.

231

232 Then we calculated the phenological differences between urban or buffer zone and
233 rural area for each city and each year separately as follow:

234
$$\Delta P = P_{ub} - P_r$$

235 where P_{ub} and P_r represent vegetation phenological metric (i.e., SOS, EOS, or GSL)
236 in urban (or buffer) and reference rural areas, respectively. ΔP is their difference for a
237 given phenological metric. A negative value of ΔP for SOS/EOS indicates an advance
238 of the SOS/EOS, while the opposite means a delay. A positive value of ΔP for GSL
239 demonstrates a prolonged growing season and vice versa. The phenological estimates
240 may vary substantially by year due to climate variability, urban development, and/or
241 varying data quality, we thus averaged the ΔP over the period 2007-2013 in order to
242 capture the overall urban-rural phenological trend for each city.

243

244 **2.3 Analysis**

245 The trends of the SOS and EOS differences (relative to unaffected rural area, hereafter)
246 from urban to rural areas were examined using an exponential decay model of
247 individual cities based on previous findings (Zhang et al., 2004; Zhou et al., 2015).
248 For the cities with significant decline trends ($p < 0.05$), we further explored their
249 relationship with temperature differences across urban and buffer zones. The
250 version-5 LST data from Aqua MODIS (MYD11A2, 8-day composite, and 1km
251 spatial resolution), monitored at 1:30 (nighttime) and 13:30 (daytime) local solar time,
252 was used in this study. The LST was retrieved from clear-sky (99% confidence)
253 observations using a generalized split-window algorithm (Wan and Dozier, 1996). It
254 has been widely validated with the bias generally less than 1 K (Wan, 2008) in most

255 cases and the mean absolute differences (relative to the in-situ measurements) less
256 than 5% in urban areas (Rigo et al., 2006). We calculated the LST differences using
257 the same method as that for phenology. Since the SOS and EOS are mainly controlled
258 by spring and autumn temperatures, respectively (Hänninen et al., 1990; Kramer,
259 1994), the correlations between the SOS/EOS differences and spring (March to May)
260 /autumn (September to November) LST differences were analyzed using SPSS (SPSS
261 Inc.).

262

263 To investigate the spatial variability of the urbanization effects on phenology across
264 cities in China, we estimated the urban-rural differences of the SOS, EOS, and GSL in
265 all six regions of China. To address the uncertainty introduced by the relatively small
266 number of cities in each region, a nonparametric resampling procedure was used to
267 generate bias-corrected bootstrap 95% confidence intervals of the phenological
268 differences from 1,000 randomizations of the observed phenological differences
269 within each region in SPSS PASW Statistics 18 (SPSS Inc.). Significance tests
270 ($p=0.05$) were then conducted to determine (1) if the estimated phenological
271 difference was statistically different from zero for each region (i.e., does the
272 urbanization effect exist?), and (2) if there were differences in phenology across
273 regions.

274

275 The relationship between spring/autumn urban-rural LST differences (refers to the
276 UHI intensities) and urban-rural SOS/EOS differences were examined by general
277 linear regression model. We also explored the climatic effects (mean annual
278 precipitation, and air temperature) on the spatial variability of the urban-rural
279 phenological differences across cities. Monthly climate data of precipitation and
280 temperature over 2007-2013 were obtained from Chinese Meteorological
281 Observations (downloaded free from <http://cdc.cma.gov.cn/>). The meteorological
282 station for each city was located in its urban area or nearby buffers (Zhou et al.,
283 2014b). We assume that the data can reflect the overall climatic background for each
284 city. Although urbanization may impact local climate to some extent, they should not
285 alter the spatial pattern of the background climate significantly (Arnfield, 2003).

286

287 **3 Results**

288 The negative SOS differences (i.e., advance) and positive EOS differences (i.e., delay)
289 averaged over the period 2007-2013 decayed exponentially and significantly ($p < 0.05$)
290 with distance away from urban edge for over half of 32 cities (i.e., 21 for SOS and 17
291 for EOS). Insignificant trends were observed for most of the remaining cities, in
292 particular for the southern cities of China (e.g., Guiyang, Guangzhou, and Shenzhen)
293 (Fig. 4). For those cities with evident trends, the SOS and EOS differences were
294 correlated negatively and positively ($p < 0.05$) with spring and autumn LST

295 differences, respectively, in most cases (Table 1). On average, one degree increase of
296 spring LST during the day and night resulted in an advance of the SOS by 11.4 ± 4.1
297 days (95% confidence intervals, hereafter) ($r = 0.91, p < 0.01$) and 8.7 ± 0.8 days ($r =$
298 $0.99, p < 0.01$), while one degree rise of autumn LST during day and night led to a
299 delay of the EOS by 9.8 ± 3.7 days ($r = 0.91, p < 0.01$) and 5.6 ± 0.4 days ($r = 1.00, p$
300 < 0.01), respectively (Fig. 5).

301

302 A great deal of spatial heterogeneities was indicated in urban-rural phenological
303 differences across cities in China (Figs. 4). The SOS advanced in urban zones
304 compared to rural areas in 27 out of 32 cities, with the SOS differences ranging from
305 -27 days in Shenyang to 19 days in Xi'an. By contrast, EOS delayed in urban area in
306 three-quarters of the cities, with the EOS differences ranging from 24 days in
307 Chengdu to -14 days in Nanning. Consequently, the GSL was longer in urban than
308 rural areas for majority of the cities (27 out of 32).

309

310 Overall, urbanization advanced the SOS in all the regions of China, with the largest of
311 -25.0 (-27.2, -22.8) days (values in parentheses define the 95% confidence interval,
312 hereafter) in Northeast China and the least of -4.7 (-9.6, 0.1) days in Central-south
313 China (Fig. 6A). Comparatively, urbanization delayed the EOS in all the regions,

314 although the delays were statistically insignificant over southeastern parts of China
315 (i.e., East China, Central-south China, and Southwest China) (Fig. 6B). Northwest
316 China and Central-south China witnessed the greatest [11.0 (6.6, 15.5) days] and least
317 [0.8 (-6.9, 9.0) days] delays, respectively. On average, SOS advanced 11.9 (-15.7,-7.7)
318 days and EOS delayed 5.4 (2.2, 8.6) days in the urban zones of the 32 cities relative to
319 adjacent rural areas. As a result, the GSL was prolonged by 17.3 (11.6, 23.1) days (Fig.
320 6C).

321

322 **4 Discussion**

323 **4.1 Trends of the urbanization effects on phenology of individual cities**

324 Our results showed that the effect of urbanization on phenology was the greatest in
325 urban centers and decreased exponentially toward rural areas for over half of the cities.
326 The findings were generally in agreement with our hypothesis and the previous
327 findings in the eastern North American (Zhang et al., 2004) and eastern China (Han
328 and Xu, 2013). We further found that the advances of SOS or the delays of EOS were
329 linked closely with LST differences for most of those cities with evident phenological
330 trends toward rural centers, characterized by a greater phenological change associated
331 with a higher temperature difference. Similar phenomenon was reported by Zhang et
332 al. (2004) in the eastern North American. This pattern was also highly consistent with
333 the well-known temporal trends of the phenology associated with warming over

334 northern mid-high latitudinal regions in recent decades (e.g., Piao et al., 2006; White
335 et al., 2009; Zeng et al., 2011; Jeong et al., 2011; Cong et al., 2012).

336

337 Overall, we identified a strong phenological sensitivity to temperature for those cities
338 with obvious phenological trends (Fig. 5), indicated by 9-11 days SOS advance and
339 6-10 days EOS delay per 1°C increase of LST in spring and autumn, respectively.
340 Zhang et al. (2004) reported 3-day SOS advance per 1°C increase in LST in the
341 eastern North America. The discrepancy might be attributed to the differences in
342 research methods, study areas, study periods, and data sources (White et al., 2009;
343 Cong et al., 2012).

344

345 **4.2 Variations of the urbanization effects on phenology across cities**

346 The urbanization effects on phenology varied across regions. The variability of the
347 urbanization effects on phenology can be also identified by comparing the latitudinal
348 trends of the phenological metrics between urban and rural areas (Fig. 7). The trends,
349 in days per 1°C latitude increase, of the urban SOS (0.75 ± 0.31 , mean ± 1 standard
350 error hereafter), EOS (0.23 ± 0.14), and GSL (-0.52 ± 0.42) were much weaker than
351 those for their rural counterparts (1.32 ± 0.50), EOS (-0.56 ± 0.23), and GSL ($-1.88 \pm$
352 0.59), respectively. These results also showed the increasing urbanization effects with

353 increasing latitudes. This generally agrees with the recent global report by Peng et al.
354 (2012) and our previous finding (Zhou et al. 2014b) that the urban heat island effects
355 overall increase with latitudes.

356

357 The background climate strongly affects the geospatial variability of urbanization
358 effects (Fig. 8). The magnitude of SOS advance and EOS delay (relative to rural
359 zones) was negatively correlated with mean annual air temperature. This phenomenon
360 can be attributed to the higher sensitivity of vegetation phenology to climate change
361 in colder regions compared to warmer zones (Nemani et al., 2003; Cong et al., 2012;
362 IPCC, 2013; Garonna et al., 2014). Moreover, the mean annual precipitation was also
363 related to the urban-rural EOS difference (Fig. 8), consistent with previous
364 observations (Zhang et al., 2004; Peñuelas et al., 2004; Cong et al., 2012; Jochner et
365 al., 2013).

366

367 Our study showed that urban heat island (i.e., UHI) intensities were positively related
368 to urban-rural SOS differences and negatively related to EOS differences across cities
369 (Fig. 8), which is the opposite found by Zhang et al. (2004). The discrepancy might be
370 caused by differences in (1) data and methods, and (2) background climate which is
371 the ultimate factor that defines the spatial patterns of UHI effects across large

372 geographical areas (Zhou et al, 2014b; Zhao et al., 2014). Global or cross-boundary
373 studies should be conducted in the future to investigate the exact reasons for the
374 difference.

375

376 Overall, the SOS advanced 11.9 (-15.7,-7.7) days and the EOS delayed 5.4 (2.2, 8.6)
377 days in urban relative to adjacent rural areas for the 32 major Chinese cities. This
378 phenomenon can be attributed to the fact that spring phenology is generally more
379 sensitive to temperature than autumn phenology (White et al., 2002; Zhang et al.,
380 2004). This pattern was consistent with the satellite observations in the eastern United
381 States (White et al., 2002) and the field observations in the cities of Europe (Mimet et
382 al., 2009; Roetzer et al., 2000) and China (Lu et al., 2006). Also, it agreed well with
383 the well-known phenological trends through time over northern mid- to high-latitudes
384 in response to global warming (e.g., Piao et al., 2006; Zeng et al., 2011; Jeong et al.,
385 2011; Cong et al., 2012), further demonstrating the suitability of using urban areas as
386 a natural laboratory to study phenological responses to global warming.

387

388 **4.3 Uncertainties**

389 Uncertainties existed in the results derived from this analysis. Several factors might
390 contribute to those uncertainties. First, we did not exclude cropland from our study.

391 The phenology of cropland depends strongly on crop type and human management
392 and is generally characterized by faster greening and earlier harvesting (Zhang et al.,
393 2004; Buyantuyeva and Wu, 2012), resulting advances of SOS (i.e., Xi'an) and EOS
394 (usually coupled with warming effect) in rural areas. The EVI in the rural areas of a
395 few cities including Xi'an, Zhengzhou and Shijiazhuang presented two evident
396 growing seasons per year because of double cropping (Fig. 9).

397

398 Second, in addition to temperature, other factors associated with urbanization such as
399 species composition, hydrological regime, photoperiod, management practices (e.g.,
400 irrigation and nutrient application), and atmospheric environments (e.g., higher CO₂
401 concentrations) may influence the phenological activities (Jach et al., 1999; Imhoff et
402 al., 2004; Zhang et al., 2004; Gazal et al., 2008; Buyantuyeva and Wu, 2012; Jochner
403 et al., 2013). For example, urban vegetation frequently includes exotic species that
404 may exhibit phenological patterns different from native plants. The urbanization effect
405 on phenology may vary by species (Jochner et al., 2013), which might contribute to
406 the large heterogeneity in phenology within a buffer or urban zone (Fig. 3). Moreover,
407 urban vegetation is usually heavily managed, which may also affect the phenological
408 patterns. Note that the number of cities with insignificant trends of the EOS (15 out of
409 32) was more than that of the SOS (11 out of 32), possibly indicating that other
410 factors unconsidered play a more important role in controlling the EOS than the SOS,

411 which was suggested by Zhang et al. (2004).

412

413 Third, data and methods may also introduce uncertainties. For example, there might
414 be significant discrepancies between MODIS and ground-based vegetation index
415 depending on climate conditions and geographic locations, especially for tropical
416 regions (Hmimina et al., 2013). In particular, the seasonal patterns of the EVI for the
417 tropical cities of China were not so evident (Fig. 9), because they are mainly covered
418 by evergreen vegetation. This might contribute to the insignificant urbanization
419 effects on phenology in many southern cities in China (Fig. 4). In addition, as
420 mentioned above, there was double growing seasons per year for some cities because
421 of the presence of double cropping (Fig. 9), and the double logistic algorithm we
422 adopted might not perform very well in this situation (Atkinson et al., 2012).
423 Moreover, we used the static land coverage maps in 2010 (Zhao et al., 2015) to
424 delineate urban and buffer areas from 2007 to 2013. This would introduce some
425 biases on the distribution of urban and buffer areas, especially for cities that
426 experienced rapid urbanization, but should not change the phenological trends.

427

428 Our study focused mainly on the impacts of urbanization on land surface phenology
429 using remotely sensed data. There is a clear need for continued phenological

430 monitoring and research in urban areas in the future using both remote sensing
431 technology and ground observations since urbanization-induced phenological shifts
432 can exert strong impacts on both the eco-environments and human health (Neil and
433 Wu, 2006) and can be used as natural laboratories to understand the impacts of future
434 changes in climate (i.e., warming) and atmospheric composition (i.e., CO₂
435 concentration). While remote sensing is helpful in quantifying phenology at an
436 ecosystem level, most issues mentioned above have to be addressed by direct
437 observations and experimental manipulations.

438

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447

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653

654 **Table 1** Spearman's correlations between the phenological and land surface
655 temperature differences relative to adjacent unaffected rural areas across urban and
656 seven buffer areas. SOS and EOS represent the start and end of growing season,
657 which were related to spring and autumn temperature differences, respectively.

City name	SOS		EOS		City name	SOS		EOS	
	Day	Night	Day	Night		Day	Night	Day	Night
Beijing			0.90 ^a	0.76 ^b	Lhasa	0.62	-0.69	0.60	0.93 ^a
Changchun	0.21	-0.69	0.62	0.62	Nanchang	-0.50	-0.95 ^a		
Changsha	-0.76 ^b	-0.38			Nanjing				
Chengdu	-0.95 ^a	-0.55	0.93 ^a	0.93 ^a	Nanning				
Chongqing	-0.95 ^a	-0.83 ^b			Shanghai	-0.86 ^b	-0.26		
Fuzhou					Shenyang	-0.33	-0.83 ^b	0.69	0.55
Guangzhou					Shenzhen				
Guiyang					Shijiazhuang	0.00	-0.62		
Haikou					Taiyuan	0.05	-0.90 ^a	0.69	0.79 ^b
Hangzhou	-0.60	-0.98 ^a			Tianjin	0.74 ^b	-0.93 ^a	-0.19	0.98 ^a
Harbin	-0.33	-0.90 ^a	0.83 ^b	0.90 ^a	Urumqi	-0.24	-0.98 ^a	-0.43	0.98 ^a
Hefei	-1.00 ^a	-0.24	0.62	0.40	Wuhan	-0.67	-0.48	0.81 ^b	0.33
Hohhot	1.00 ^a	-0.93 ^a	-0.62	0.79 ^b	Xi'an				
Jinan			0.24	0.90 ^a	Xining	-0.36	-0.98 ^a	0.93 ^a	0.88 ^a
Kunming	-0.52	-0.98 ^a			Yinchuan	-0.05	-0.67	0.33	0.45
Lanzhou	0.95 ^a	-0.83 ^b	-0.86 ^b	0.79 ^b	Zhengzhou			0.79 ^a	0.93 ^b

658 Day and Night represent the relationships with daytime and nighttime land surface
659 temperature differences, respectively;
660 “ ”, an insignificant trend of the phenological differences toward rural areas;
661 ^a, significant at 0.01 level;
662 ^b, significant at 0.05 level.

663

664 **Figure Captions**

665 **Figure 1** Locations of the 32 major cities and six geographic regions in China, with
666 the background indicating the vegetation map of China (this data set is provided by
667 “Environmental & Ecological Science Data Center for West China, National Natural
668 Science Foundation of China” (<http://westdc.westgis.ac.cn>)). All of the cities are
669 municipalities or provincial capitals except Shenzhen, which is China's first special
670 economic zone established in 1978, and is now considered one of the fastest-growing
671 cities in the world. Albers Conical Equal Area was used as the projection coordinate
672 system.

673 **Figure 2** Concept map shows the start of growing season (SOS) and the end of
674 growing season (EOS) that were defined as 20% of the seasonal amplitude measured
675 from the left and right minimum levels, respectively.

676 **Figure 3** The delineation of urban land cover, EOS day (day of year), EOS day (day
677 of year), and seven buffer zones in the year 2010, an example of Beijing. Pixels that
678 were water body or with elevation more than 50 m higher than the highest point in
679 urban area were excluded from this analysis.

680 **Figure 4** Trends of the SOS and EOS differences relative to adjacent unaffected
681 reference toward rural areas. The green and red lines represent the exponential fit
682 curve of the SOS and EOS differences ($p < 0.05$) with distance away from urban areas,

683 respectively. The error bars represent one standard deviation across years.

684 **Figure 5** linear regression slope (95% confidence intervals) between the SOS/EOS
685 and land surface temperature (LST) differences (relative to rural areas) across urban
686 and buffer (left to right, buffer 7 to 1) areas averaged over those cities that exhibited
687 significant phenological trends ($p < 0.05$) toward rural areas. The error bar represents
688 one standard deviation.

689 **Figure 6** The urban-rural differences of the SOS, EOS, and growing season length
690 (GSL) in different geographic regions. The horizontal lower and upper error bars
691 represent the minimum and maximum values, respectively.

692 **Figure 7** Latitudinal trends of the SOS, EOS, and GSL in urban and rural areas for
693 China's 32 major cities. S represents the linear slope. The bias-corrected bootstrapped
694 standard error (based on 1000 bootstrap samples) was estimated for each slope.

695 **Figure 8** Relationship between climatic factors or urban heat island intensity (UHII,
696 urban-rural LST difference) and the urban-rural differences () of SOS/EOS across
697 China's 32 major cities.

698 **Figure 9** Intra-annual variations of the smoothed enhanced vegetation index in urban
699 area and seven buffers (i.e., Buffer1 to Buffer7) for China's 32 major cities averaged
700 over 2007-2013.

Figure 1

Figure 2

Figure 5

Figure 6