

# 1 Urbanization effects on the spatial 2 patterns of spring vegetation phenology 3 depend on the climatic background

## 4 5 **Abstract:**

6 Urbanization is one of the most severe human interventions that alter the natural ecosystem  
7 and lead to various environmental changes. Spring vegetation phenology (i.e., leaf unfolding)  
8 has been emphasized as an important indicator to observe changes in the Earth's climate  
9 system. The earlier initiation of leaf unfolding responses to physical urban warming has been  
10 reported, but no detailed quantification of urbanization and climatic peculiarities effects on  
11 spring phenology for the rural-urban ecosystem. Here, we employ impervious surface area  
12 percentage as a metric of urbanization level and link geographical climate constraints with  
13 plant phenology to investigate how leaf unfolding shifts in response to different urban  
14 environments and climatic peculiarities. Our results suggest that the urbanization-induced  
15 urban heat island (UHI) effects cause the advancement of leaf unfolding, and this advanced  
16 trend varies across different climate zones. The leaf unfolding time is highly linearly  
17 correlated with urbanization levels at China's mid-latitudes (around 30 °C), where the climate  
18 (temperature and humidity) is moderate. Regionally, the leaf unfolding timing is north-south  
19 symmetrical for the rural-urban phenology on the national scale. Divergent requirements of  
20 chilling accumulation, high forcing temperatures, and plants adaption ability jointly drive this  
21 phenomenon. As the UHI effects and climatic peculiarities are discernible in plant  
22 populations in the rural-urban ecosystem, understanding the general phenology responses to  
23 climatic environment changes in the integral rural-urban system will have implications for the  
24 climate change impact on ecosystems globally.

## 25 **Keywords:**

26 Leaf unfolding; rural-urban ecosystem; climate; urban heat island; remote sensing

## 27 **1. Introduction**

28 Global warming is accelerating rapidly due to the rising emissions of greenhouse gases from  
29 the intensifying urbanization (Latif & Keenlyside, 2009; Trenberth et al., 2015; Xu et al., 2018).  
30 Extreme weather events consequently accompanied by global warming are frequently  
31 emerging (Coumou & Rahmstorf, 2012; Diffenbaugh et al., 2017; Field & Barros, 2014;  
32 Trenberth et al., 2015), which could substantially reshape the ecological resilience (Field &  
33 Barros, 2014), e.g., influence on ecological community (Allen et al., 2014; Griggs & Noguera,  
34 2002; Ogunbode et al., 2020) and the diversity of ecosystems and species (Bakkenes et al.,  
35 2002; Watson, 1996; Woodward & Woodward, 1987). As the Intergovernmental Panel on  
36 Climate Change (IPCC) has reported, maintaining and limiting global warming of 1.5 °C is

37 vital (Masson-Delmotte et al., 2018). So, it is necessary to efficiently make use of reliable  
38 observations to indicate and evaluate the impact of climate change on a large scale.

39 Plants can respond to climate change by shifting their phenological time correspondingly.  
40 Particularly, leaf unfolding, sensitive to the cumulative effects of temperature over a period  
41 (Badeck et al., 2004; Körner & Basler, 2010; Myneni et al., 1997; Peñuelas & Filella, 2001), is a  
42 widely-used diagnostic indicator of global climate change (Morisette et al., 2009; Parmesan &  
43 Yohe, 2003; Schwartz et al., 2006). Although researchers have used numerous techniques to  
44 observe the phenological changes for plants, such as in-situ observations for individual  
45 species (Menzel et al., 2006; Walther et al., 2002) and networked digital cameras (e.g.,  
46 PhenoCam) (Graham et al., 2010; Keenan et al., 2014; Richardson et al., 2009), the investigation  
47 of an environmental change on vegetation phenology requires repeated measurements over a  
48 large area and a long period (Morecroft & Keith, 2009). Such need is partially addressed by the  
49 rapid development of remote sensing technology that has offered possibilities to monitor plant  
50 phenology across broad spatiotemporal scales (Pettorelli et al., 2005; Piao et al., 2019; Zhang et  
51 al., 2003). Climate change is thus detectable through the remotely sensed phenological  
52 observations in tracking rapid global warming.

53 Urban, one of the most rapid types of land cover change, is the main driver for environmental  
54 changes across scales (Gao & O'Neill, 2020). It is a natural laboratory providing complicated  
55 environmental conditions associated with human activities, which can predict ecosystem  
56 sustainability under extreme climate events caused by global warming (Zhao et al., 2016). The  
57 distinct changes in the land surface caused by the urbanization process modified the regional  
58 climate properties, making urban experience higher temperatures than rural areas, known as  
59 the urban heat island (UHI) effect (Landsberg, 1981). Such temperature changes can  
60 significantly influence the physical environment of plants and, thus, shift their phenological  
61 time.

62 The phenological events are feedback from the multiple and intricate links between the  
63 ecosystem and climate system. Global climate change could change the leaf unfolding date of  
64 plants via temperature (Cleland et al., 2007). Those changes in spring vegetation phenology  
65 can physically modify the surface energy balance and bring challenges in ecological  
66 circulation regimes (Morisette et al., 2009). Climate change also impacts the leaf unfolding  
67 date, extending or narrowing the growing season length, thus influencing the carbon uptake in  
68 the terrestrial ecosystem (Gu et al., 2003; Piao et al., 2017; Richardson et al., 2009).  
69 Additionally, global warming and resultant earlier occurrence of flowering can increase the  
70 risk of pollen-induced allergy and affect public health (Li et al., 2019). As plant phenology  
71 integrates the interaction between climate and biosphere (Foley et al., 1996; Hufkens et al.,  
72 2018; Morisette et al., 2009), documenting and evaluating the effects of climate change on  
73 plant phenology can provide supportive understandings in predicting biological responses to  
74 future climate scenarios (Schwartz et al., 2006).

75 Numerous studies have used various datasets nationally or based on city scales to discuss the  
76 phenological difference between urban and rural counterparts during the last several decades  
77 (Jia et al., 2021; Meng et al., 2020; Zhang et al., 2004; Zhao et al., 2016; Zhou et al., 2016).  
78 However, these efforts only focused on the local temperature attribution (UHI effects) to this

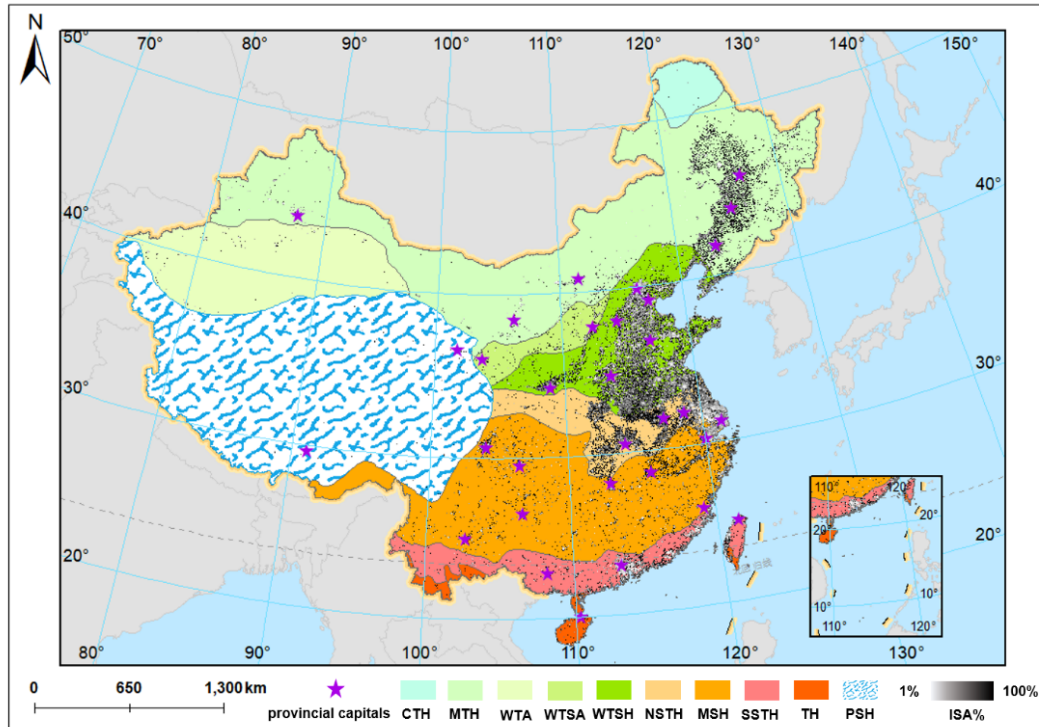
79 difference rather than geographically climatic peculiarities in terms of the scale of rural-urban  
80 ecosystems. Also, they lacked trends depicting the detailed phenological response along the  
81 rural-urban gradients so that the interaction between phenology and urbanization cannot be  
82 fully assessed. Most importantly, the definition between rural and urban is unclear, leading to  
83 differences in rural and urban phenological calculations between studies. For example, the  
84 land use percentage of urban was used to define the rural (less than 1%) and urban areas  
85 (more than 50%) (Jia et al., 2021), while in another study, 20-25 km buffer from the urban  
86 edge was regarded as rural areas (Zhou et al., 2016). Furthermore, those previous studies did  
87 not exclude crop influence, which can significantly contribute to the rural-urban phenological  
88 difference. While the causal link between temperature and phenology is conceptually  
89 straightforward and the global climate warming and UHI effects at the regional scale are well  
90 documented (Jin et al., 2005; Solecki et al., 2005; Yang et al., 2011), the potentially mutual  
91 effects on urbanization, climate change, and spring phenology are less understood. China has  
92 undergone extensive land cover/land-use change rapidly and spans several climate zones,  
93 providing an excellent opportunity to explore the interplay between urbanization, phenology,  
94 and climate change.

95 In this study, we used impervious surface area (ISA) percentage as an indicator of  
96 urbanization level, combining urbanization-related land surface temperature (LST) and air  
97 temperature, under the regionally climatic constraints of temperature and humidity, to answer  
98 the following questions at spatial resolution and extents relevant to mesoscale: (1) How does  
99 plant spring phenology respond to different levels of urbanization? (2) How do climatic  
100 peculiarities impact the spring phenology in the rural-urban ecosystem? (3) What is the  
101 mechanism behind the interplay among urbanization, climate change, and spring phenology?

## 102 **2. Materials**

### 103 **2.1 Study area**

104 We studied the whole territory of China, covering a total of 347 cities (including major  
105 counties) across ten climatic diversity zones (Figure 1). The climate zone dataset was  
106 obtained from the Resource and Environment Science and Data Center (RESDC) of the  
107 Chinese Academy of Science (CAS) (<https://www.resdc.cn/>). We statistically analyzed the  
108 thermal difference between rural and urban through all cities in China to investigate the  
109 urbanization effects on leaf unfolding across various climate zones and 32 major cities  
110 (municipalities and provincial capitals), the most highly urbanized regions in China.



111

112 **Figure 1. The distribution of climate zones and impervious surface area (ISA) percentage in**  
 113 **China.** CTH, cold temperate & humid zone; MTH, mid-temperate & humid zone; WTA, warm  
 114 temperate & arid zone; WTSA, warm temperate & semi-arid zone; WTSH, warm temperate &  
 115 semi-humid zone; NSTH, northern subtropical & humid zone; MSH, mid-subtropical & humid  
 116 zone; SSTH, southern subtropical & humid zone; TH, tropical & humid zone; PSH, plateau &  
 117 semi-humid zone.

118 **2.2 Remotely sensed leaf unfolding dates**

119 We obtained phenological observations from VIIRS (Visible Infrared Imaging Radiometer  
 120 Suite) Global Land Surface Phenology Product (GLSP) (VNP22Q2, Collection 1), which uses  
 121 a hybrid piecewise logistic function to track the phenological transition dates by the two-band  
 122 enhanced vegetation index (EVI2) (X. Zhang et al., 2018). The VIIRS phenology dataset has  
 123 been evaluated using four datasets at different scales (i.e., the national phenological networks,  
 124 the Landsat, MODIS, and PhenoCam observations), suggesting this dataset can precisely  
 125 characterize the phenological dynamics and changes (Zhang et al., 2018). We converted the  
 126 raw record to the day of the year (DOY) and defined the onset time of greenness increase as  
 127 leaf unfolding date at which the EVI2 value close to the minimum greenness during a  
 128 growing season.

129 **2.3 Urbanization level indicated by ISA data**

130 We derived the grid-scale (1km) urbanization level using the global artificial impervious area  
 131 (GAIA) data. The GAIA data were generated using the full archive of Landsat images with a  
 132 spatial resolution of 30 m (Gong et al., 2020). The mean overall accuracy of GAIA is above  
 133 90%, and the urban expansion in GAIA is temporally consistent (Li et al., 2015). To match the  
 134 resolution with other datasets, we aggregated the GAIA data to 1km in the proportional form

135 of ISA as a proxy to quantitatively characterize urbanization levels.

## 136 **2.4 Temperature datasets**

137 We derived the LST data from the Moderate Resolution Imaging Spectroradiometer (MODIS)  
138 LST product with a spatial resolution of 1km as the forcing temperature driving leaf  
139 unfolding. Cloudy observations in the LST product were excluded before the analyses. Here,  
140 we preferred LST over air temperature as a driving force behind leaf unfolding for two  
141 reasons. First, the LST is tightly correlated with urbanization (Imhoff et al., 2010) and is  
142 significantly related to spring phenology (Zhou et al., 2016). Second, the spatial resolution of  
143 available daily air temperature data is relatively coarse (e.g., 10km) (He et al., 2020), making  
144 it difficult to reflect vegetation phenology differences along the rural-urban gradient.

145 The air temperature plays an essential role in determining the dormancy release and leaf  
146 unfolding. To acquire background temperature for calculating chilling requirements before  
147 leaf unfolding, we obtained the daily mean air temperature with a spatial resolution of 0.1°  
148 (around 10km) from the China Meteorological Forcing Dataset (Yang & He, 2019). However,  
149 we did not calculate the chilling requirement for leaf unfolding under each urbanization  
150 gradient due to its relatively coarse spatial resolution. Instead, we applied air temperature  
151 rather than LST to explore the physical process-based mechanism behind the phenological  
152 leaf unfolding across different climate zones because numerous studies have already  
153 suggested the optimal air temperature range for leaf unfolding to meet the chilling  
154 requirement (Coville, 1920). Given that there are distinct divergences between LST and air  
155 temperature (Benali et al., 2012) and no relative existing experiments have proposed the  
156 proper range for LST to calculate the chilling requirement, we did not use LST to calculate  
157 chilling requirements along the rural-urban gradient.

## 158 **2.5 Auxiliary data and preprocessing**

159 Before analyzing, we abated the effect of cropland and water on rural-urban phenological leaf  
160 unfolding. We used the Climate Change Initiative land cover (CCI-LC) data with a spatial  
161 resolution of 300 m that was released by the European Space Agency (ESA)  
162 (<https://www.esa-landcover-cci.org/>). We selected the CCI- LC types labeled with cropland  
163 (rainfed cropland, irrigated or post-flooding cropland, and mosaic cropland greater than 50%)  
164 and water to aggregate them to 1 km resolution in the form of proportions of crop area and  
165 water area and removed the pixels with proportions above 50% of cropland and water in our  
166 analyses. Furthermore, we aggregated all sets of datasets (except for the air temperature) into  
167 1 km to match the resolution of LST. We chose the period from 2013 to 2018 that are  
168 available by all the datasets as our study time scope and then calculated the mean over six-  
169 year to minimize the effects of outlier observations. Besides, another reason for taking mean  
170 is that our primary goal is to examine the geospatial, not temporal, effect of rural-urban  
171 gradients of leaf unfolding.

## 172 **3. Methods**

### 173 **3.1 Variable control: temperature and humidity**

174 We controlled the environmental variables (temperature, humidity, and vegetation types) that

175 may influence the phenological leaf unfolding in our analyses. We used the Eco-geographical  
 176 division criteria provided by the RESDC to split the climatic zones into subordinate  
 177 categories according to temperature, humidity, and vegetation types. In total, we categorized  
 178 China into ten climate zones (Table 1). Additionally, we merged climate zones and renamed  
 179 their labels with the same name as the zone with the largest proportions of ISA. For example,  
 180 we combined all humidity belts in the plateau and named it the plateau semi-humid zone  
 181 (PSH) because most of the ISA locations belong to the semi-humid attribute, so do the mid-  
 182 temperate humid and warm temperate semi-humid zone. Thus, we have ensured the  
 183 homogeneity and uniformity of climatic peculiarities for each local-scale region regarding  
 184 their temperature, humidity, and vegetation types by controlling the variables. We assumed  
 185 that other factors (e.g., soil characteristics, sunlight time) are similar within each climate  
 186 zone. Thus, changes in leaf unfolding date are likely mainly determined by the urbanization-  
 187 induced UHI effect.

**Table 1.** Climate zones for vegetation spring phenology analysis in the rural-urban ecosystem.

Name	Climatic	Humidity	Days $\geq 10^{\circ}\text{C}$ (days)	Accumulated temperature ( $\geq 10^{\circ}\text{C}$ ) ( $^{\circ}\text{C}$ )	Drying index
CTH	Cold temperate	humid	< 100	< 1600	0.50 ~ 0.99
MTH	Mid-temperate	humid	100 ~ 170	1600 ~ 3200 (3400)	0.50 ~ 0.99
WTSH	Warm temperate	semi-humid	171 ~ 220	3200 ~ 4500 (4800)	1.00 ~ 1.49
WTSA	Warm temperate	semi-arid	171 ~ 220	3200 ~ 4500 (4800)	1.5 ~ 4.00
WTA	Warm temperate	arid	171 ~ 220	3200 ~ 4500 (4800)	$\geq 4.00$
NSH	Northern subtropical	humid	220 ~ 239	4500 ~ 5100 (5300)	0.50 ~ 0.99
MSH	Mid-subtropical	humid	240 ~ 285	5100 (5300) ~ 6400 (6500)	0.50 ~ 0.99
SSH	South-subtropical	humid	286 ~ 365	6400 (6500) ~ 8000	0.50 ~ 0.99
TH	Tropical	humid	365	8000 ~ 9000	0.50 ~ 0.99
PSH	Plateau	semi-humid	50 ~ 120	—	1.50 ~ 5.00

### 188 3.2 Urbanization effect on leaf unfolding

189 To explore the effect of urbanization on phenological leaf unfolding, we performed the linear  
 190 regression analysis (Eq 1) of the leaf unfolding dates against ISA over China's whole territory  
 191 and across different climatic zones.

$$192 \quad D_{LU} = \beta_{LU} ISA + \varepsilon \quad (1)$$

193 where  $D_{LU}$  is the leaf unfolding day,  $\beta_{LU}$  is the coefficient (days per 1% ISA) representing the  
 194 phenological response to the urbanization level,  $\varepsilon$  is the leaf unfolding day in the rural area.

### 195 3.3 The response of leaf unfolding to LST

196 We analyzed the sensitivity of leaf unfolding date to LST through the linear regression  
 197 approach (Eq 2). Given that the temperature is the most important trigger of spring phenology

198 (Friedl et al., 2014) and the timing of leaf unfolding varies across spaces, the spring  
 199 temperatures that are closely related to phenology are different across regions. Hence, we  
 200 defined the spring temperature as the mean temperature within their specified periods from  
 201 the earliest to the latest occurrence of leaf unfolding in each zone (Table S1). In addition, to  
 202 quantify the urbanization effect on spring phenology, we compared the difference of LST  
 203 between the rural (ISA<5%) and urban (ISA>85%) for all the cities and major counties in  
 204 China.

$$205 \quad D_{LU} = \beta_{TLU} LST + \varepsilon \quad (2)$$

206 where  $D_{LU}$  is the leaf unfolding day,  $\beta_{TLU}$  is the coefficient (days per 1% LST) representing  
 207 the phenological response to the LST along the rural-urban gradient,  $\varepsilon$  is the initial LST in the  
 208 rural area.

### 209 3.4 Leaf unfolding with chilling accumulation

210 We calculated the chilling requirement to physically understand the reason behind the  
 211 difference of leaf unfolding across climate zones. Previous studies have suggested that the air  
 212 temperature between 0 °C and 5 °C is optimal for the chilling requirement (Coville, 1920). We  
 213 calculated the average chilling accumulation days per pixel from 1 November in the year  
 214 before leaf unfolding to the minimum date of leaf unfolding for each climate zone,  
 215 respectively (see Eqs. 3-4).

$$216 \quad CD_{req}(t) = \sum_{t_0}^{t_{LU}} \begin{cases} 1, & \text{if } 0 \leq T_t \leq 5 \\ 0, & \text{otherwise} \end{cases} \quad (3)$$

$$217 \quad \bar{D}(t) = \frac{\sum_1^{100} S_{CD(i)}}{\sum_1^{100} S_{ISA(i)}} \quad (4)$$

218 where  $CD_{req}$  is the chilling accumulation days,  $t_{LU}$  is the day of leaf unfolding,  $T_t$  is the daily  
 219 mean air temperature on day t, and is the start date for chilling accumulation;  $\bar{D}$  is the average  
 220 chilling accumulation days per 1% ISA,  $S_{CD(i)}$  is the sum of chilling accumulation days for  
 221 the  $i_{th}$  ISA interval,  $S_{ISA(i)}$  is the sum of pixel numbers for the  $i_{th}$  ISA interval.

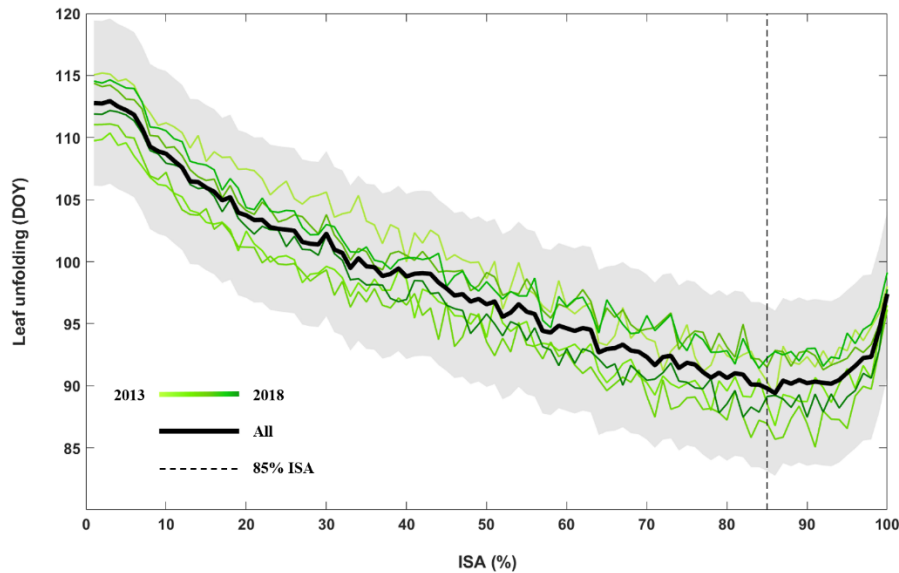
## 222 4. Results

### 223 4.1 Urbanization effects on the spring phenology

224 The leaf unfolding dates advance as the percentage of ISA increases, indicating that  
 225 urbanization is altering environmental factors that may be crucial to vegetation growth  
 226 (Figure 2). Although the overall phenological leaf unfolding patterns through the rural-urban  
 227 gradient from 2013 to 2018 are similar, there are no distinct temporal correlations, perhaps  
 228 due to limited numbers of available remotely sensed datasets. Previous studies also supported  
 229 this finding, though they studied North America (Reed, 2006; White, 2009), which are likely  
 230 associated with large interannual variations of phenology (Liu & Zhang, 2020). The leaf  
 231 unfolding dates become earlier along the rural-urban gradient for all six years, suggesting a  
 232 significant phenology difference between rural and urban areas. Hence, we focused on the  
 233 average of six-year observations to explain the relationship between leaf unfolding and  
 234 urbanization.

235 Contrary to common sense, we also noticed that leaf unfolding shows a delaying trend over

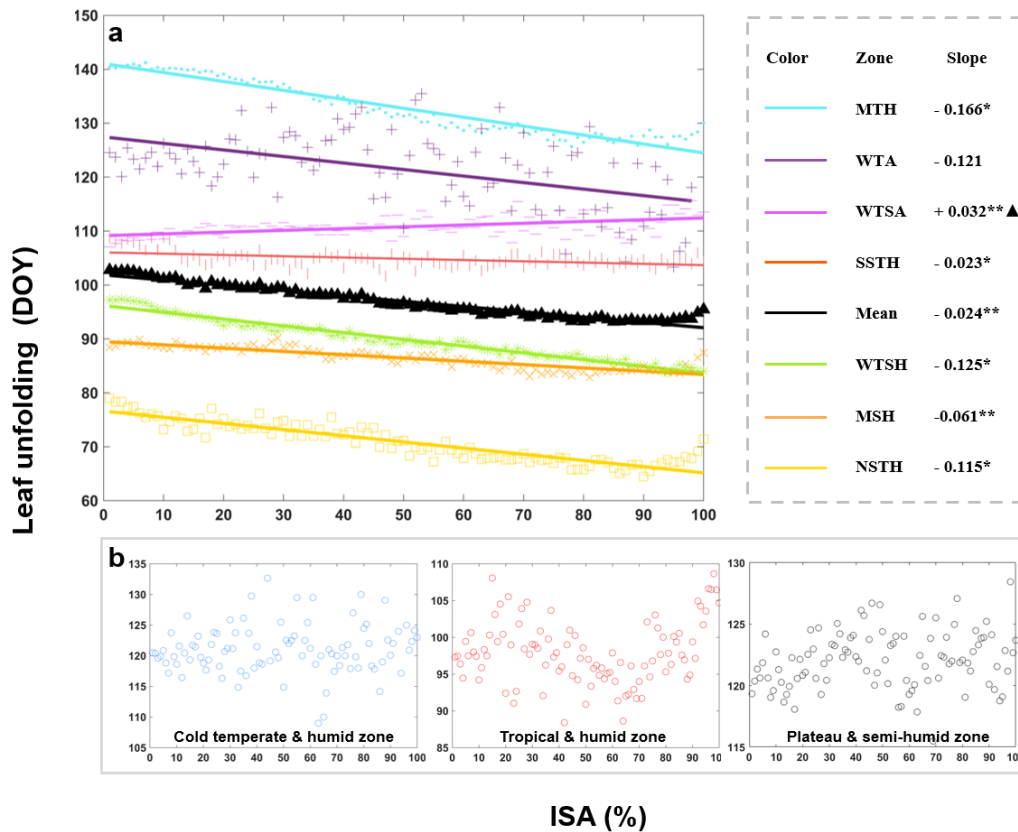
236 the high urbanization level (started from the 85% ISA). We hypothetically proposed that the  
 237 national pattern of phenological leaf unfolding is attributed to the multi-regional  
 238 heterogeneity with diverse climatic peculiarities. The phenological leaf unfolding depends on  
 239 various environmental variables such as temperature, precipitation, photoperiod, and species  
 240 (Way et al., 2015). Therefore, the entire national pattern of urban phenology, consisting of  
 241 various regions of heterogeneous phenological features, is unlikely to be a proxy that  
 242 accurately captures the characteristics of local regions.



243  
 244 **Figure 2.** The response of leaf unfolding to urbanization levels indicated by ISA along the  
 245 rural-urban gradients from 2013 to 2018. The solid black line indicates the averaged pattern  
 246 across all years, and the grey area indicates uncertainty regions with one standard deviation on  
 247 either side of the mean.

#### 248 4.2 Response of spring vegetation phenology to urbanization over various climate zones

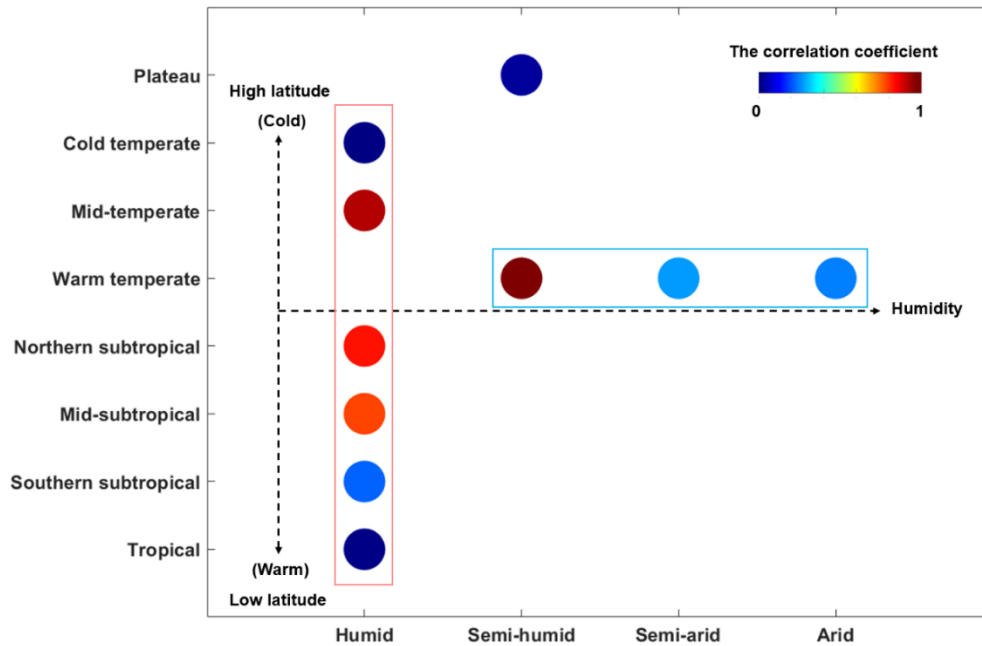
249 At the regional scale with different climatic peculiarities, we found that the phenological leaf  
 250 unfolding exhibits divergent responses to the urbanization in different climate zones (Figure  
 251 3). The leaf unfolding dates in different climate zones contribute differently to the overall  
 252 trend across China. For instance, some climate zones (e.g., WTSH, MSH, and NSTH zones)  
 253 are earlier than the national average, while others (e.g., MTH, WTA, WTSA, and SSTH  
 254 zones) are later. We also noticed that the leaf unfolding dates negatively correlate with  
 255 urbanization for most climate zones, indicating the urbanization advances the date of leaf  
 256 unfolding in general (Figure 3a). WTSA is an exception to this general pattern. Given that its  
 257 topography is the hilly loess plateau, variables other than temperature, humidity, and  
 258 vegetation types may account for the distinct pattern. The pattern between leaf unfolding and  
 259 urbanization in the CTH and TH zones located in the northernmost and southernmost of  
 260 China statistically exhibit less evident linear relationship, so does the plateau zone (Figure  
 261 3b).



262

263 **Figure 3.** The response of leaf unfolding to urbanization levels along the rural-urban  
 264 gradients in each climate zone. The linear relationship between leaf unfolding and urbanization  
 265 levels in seven climate zones (a). The back line and solid triangle indicate the average results for  
 266 the whole China mainland. Results in the remaining three zones are presented in (b). The solid  
 267 black triangle indicates positive values. The asterisk indicates the omitted decimal. **Notes:**  
 268 WTSA, warm temperate & semi-arid zone; WTSH, warm temperate & semi-humid zone; NSTH,  
 269 northern subtropical & humid zone, MSH, mid-subtropical & humid zone; SSTH, southern  
 270 subtropical & humid zone.

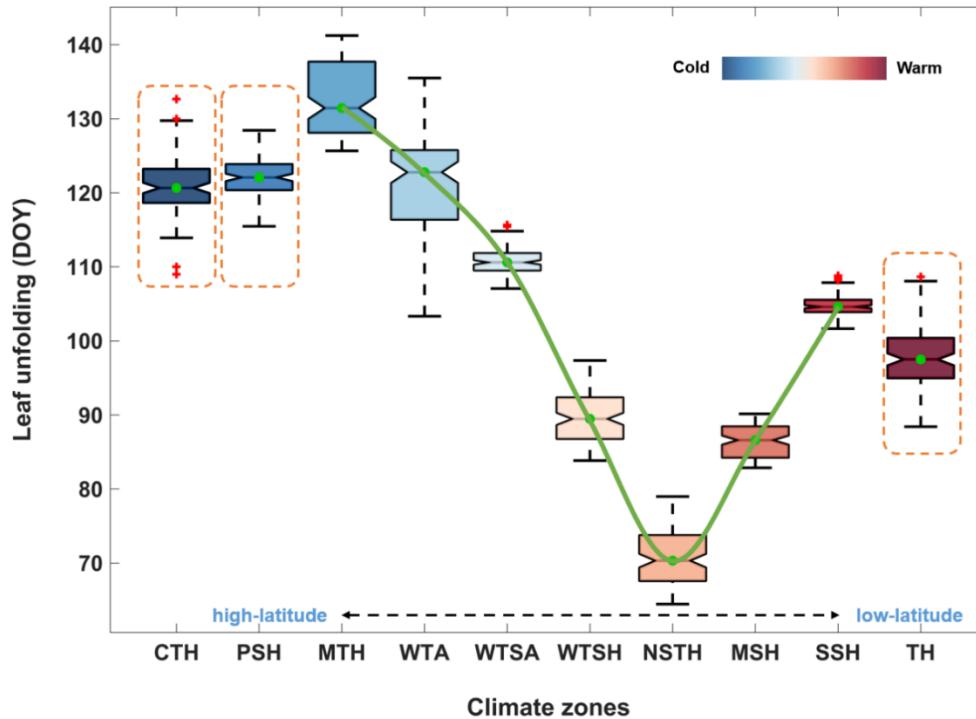
271 Mild temperature and moist environment can depict the relationship between phenological  
 272 leaf unfolding and urbanization level (i.e., ISA) in a linear manner (Figure 4). The results  
 273 show that the linear correlation coefficient between the leaf unfolding date and ISA in the  
 274 climate zones with mild temperature environments is greater than the zones with relatively  
 275 colder and warmer temperatures, related to latitude (see the red frame in Figure 4). The linear  
 276 correlation decreases from mid-latitude to the low and high-latitude regions of China,  
 277 respectively. The humidity also plays an important part in the response of leaf unfolding to  
 278 the urbanization (i.e., ISA) when the temperature is similar (see the blue frame in Figure 4).  
 279 In the same warm temperate zone, we found that the linear correlation between leaf unfolding  
 280 date and urbanization level is more robust in the humid environment than in the arid.  
 281 However, this pattern does not suit for explaining the phenomena in the PSH zone.



282

283 **Figure 4. The linear correlation coefficient between leaf unfolding and urbanization degrees**  
 284 **for each climate zone.** The dot color represents the linear correlation coefficient. The horizontal  
 285 dotted line with arrows indicates the humidity levels, and the vertical indicates the temperature  
 286 levels.

287 We also discovered that urban vegetation's phenological leaf unfolding date is related to the  
 288 temperature and latitude (Figure 5). The earliest leaf unfolding dates occurred at the mid-  
 289 latitude climate zone (NSH). Afterward, the leaf unfolding date shows a delaying trend  
 290 toward the low and high-latitude except for relatively colder (CTH and PSH) and warmer  
 291 climate zone (TH). This trend is latitudinally symmetrical in the mainland of China, on which  
 292 most climate zones agree, yet other zones such as WTSA, TH, and PSH exhibit reverse.



293

294

295 **Figure 5. The average time of leaf unfolding across different climate zones.** The box color

296 represents the background climate. The green filled color indicates the medium DOY of leaf

297 unfolding. The green line indicates the timing trend of the leaf unfolding. The central marks

298 indicate the median, and the bottom and top edges of boxes indicate the 25<sup>th</sup> and 75<sup>th</sup> percentiles,

299 respectively. The whiskers extend to the most extreme data points not considered outliers, and the

300 outliers are plotted individually using the '+' symbol. **Notes:** CTH, cold temperate & humid zone;

301 PSH, plateau & semi-humid zone; MTH, Mid-temperate & humid zone; WTA, warm temperate &

302 arid zone; WTSA, warm temperate & semi-arid zone; WTSH, warm temperate & semi-humid

303 zone; NSTH, northern subtropical & humid zone, MSH, mid-subtropical & humid zone; SSSH,

304 southern subtropical & humid zone; TH, tropical & humid zone.

### 304 4.3 Phenological temperature sensitivity

305 After adding the temperature variable, we found that phenological leaf unfolding dates are

306 negatively correlated with the LST (Figure 6). There is a significant difference in LST

307 between the rural and urban areas, and this finding is pretty robust across different years

308 (Figure S1). Therefore, the advancement of leaf unfolding caused by urbanization results

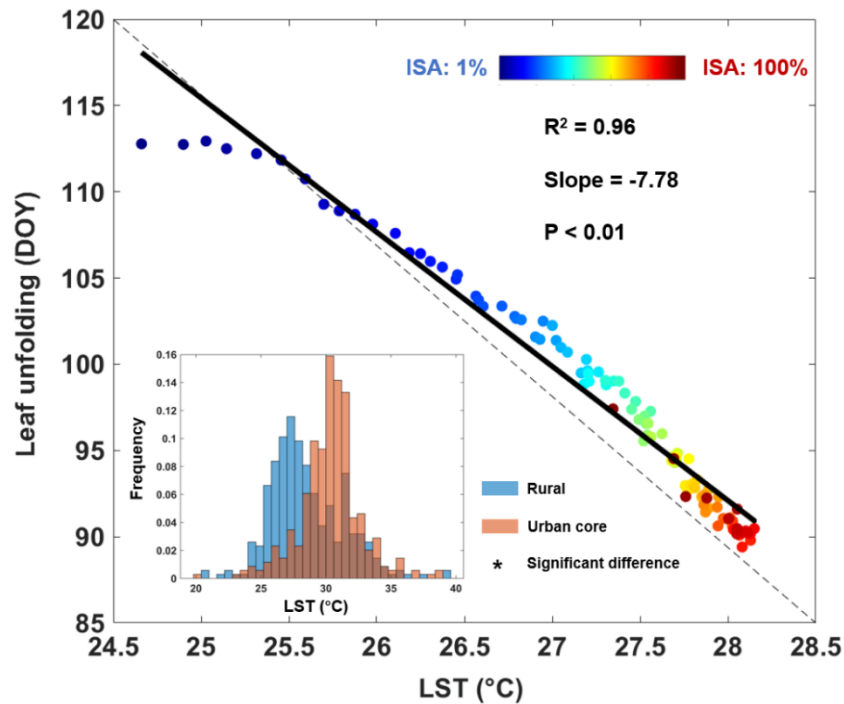
309 from the gradually increased LST from rural to urban. In general, the sensitivity of the leaf

310 unfolding date to LST is about 7.8 days/°C. However, the magnitude of this advancement

311 decreases as the increase in LST (the linear regression line is above the dotted grey line)

312 along the rural-urban gradients, suggesting the weakened response of the leaf unfolding to

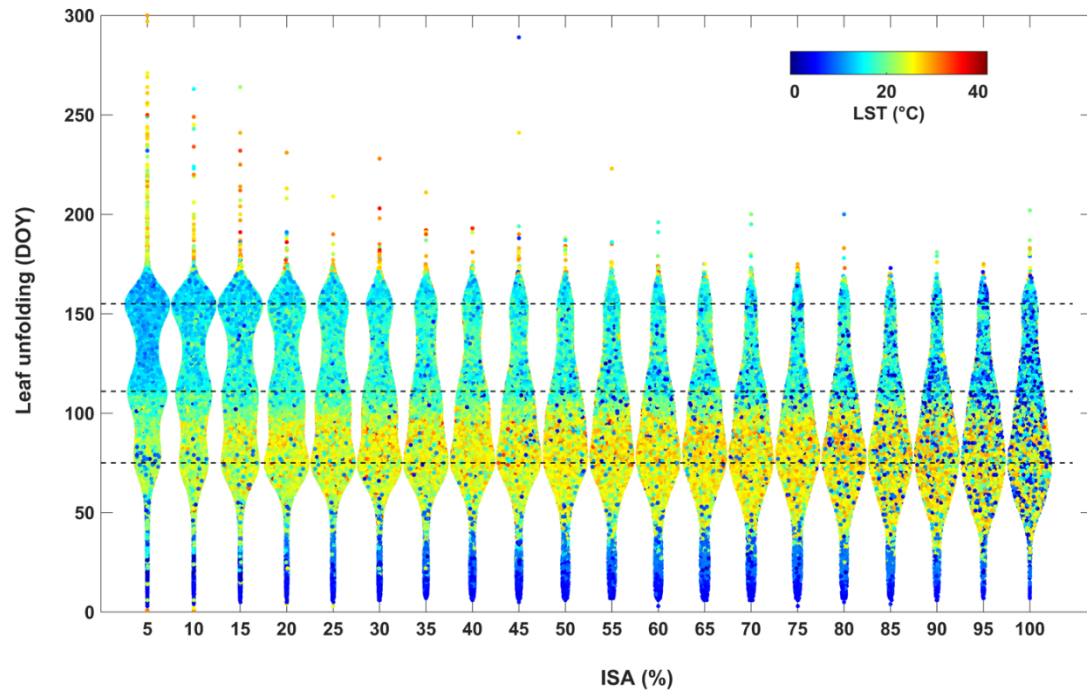
313 environmental warming.



314

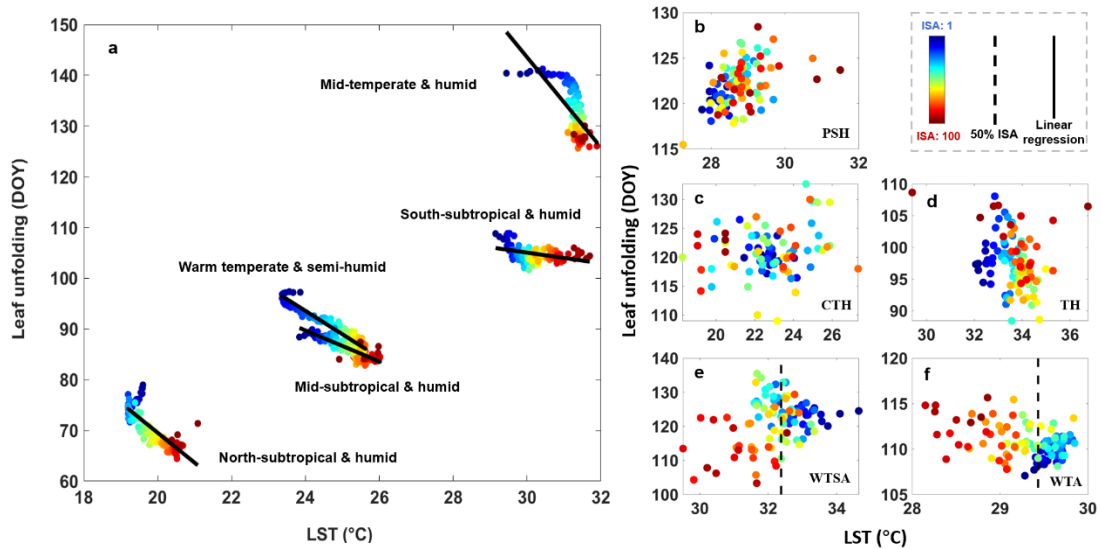
315 **Figure 6.** Change of leaf unfolding with the increase of LST with diverse urbanization levels  
 316 indicated by ISA. Point color represents background LST. The solid black line indicates the  
 317 linear relationship between leaf unfolding and LST along the rural-urban gradients. The dotted  
 318 grey line represents the 1: 1 line. The histogram indicates the LST difference between rural (i.e.,  
 319 ISA < 5%) and urban (i.e., ISA > 85%) in 347 cities. The asterisk indicates a significant level with  
 320 a *P*-value below 0.01.

321 On the national scale, the time of leaf unfolding is distributed differently along the rural-urban  
 322 gradient (Figure 7). It exhibits similarities and homogeneity in the environment of high-  
 323 degree urbanization, which is symmetrical around the only central peak and tapers off equally  
 324 in both directions. However, the responding LST to leaf unfolding changes heterogeneously,  
 325 assumably suggesting the LST caused by the complex urban environments do not necessarily  
 326 affect spring phenology much. For the rural regions, the time of leaf unfolding distributes  
 327 inhomogeneously, intensively around DOY ranges between 110 DOY and 155 DOY. Its  
 328 corresponding LST is relatively low in the peaks of bimodal normal distribution compared to  
 329 those in the high-urbanization degree. We also noticed that pixels with DOY range between  
 330 110 and 155 decreases from rural to urban, while the number of pixels with DOY centered  
 331 around 75 increases, which can be elucidated by either the changes of vegetation types or the  
 332 adaptive capability plants.



333  
 334 **Figure 7.** The distribution of leaf unfolding and LST per 5% ISA interval. Point color  
 335 represents background LST. The dotted lines indicate the three (i.e., 75, 110, and 115) most  
 336 clustered distributions of leaf unfolding time.

337 Even though the leaf unfolding date, ISA percentage, and LST are highly related on the  
 338 national scale, their correlations vary with climate zones (Figure 8). The linear correlations  
 339 among those three variables are still strong in the climate zones with proper temperature and  
 340 humidity, while other climate zones with relatively colder or warmer environments exhibit  
 341 divergently (Figure 8a). For instance, the UHI effect induced by urbanization is unobservable  
 342 in the PSH and CTH zone, where the urbanization does not advance phenological leaf  
 343 unfolding dates (Figure 8, b-c). Although the LST increases from rural to urban in the TH  
 344 zone, the leaf unfolding date is independent of urbanization and LST (Figure 8d). Most  
 345 notably, the urban cold island (UCI) effect happens in the arid zones (WTSA and WTA),  
 346 where the LST increases along the rural-urban gradient. However, the leaf unfolding reacts  
 347 differently in these arid zones (Figure 8, e-f). Even though LST decreases in the WTSA zone  
 348 with the increase of ISA, the leaf unfolding date advances earlier in the urban core than in the  
 349 rural (Figure 8e). On the contrary, the WTA zone shows a delayed trend of leaf unfolding  
 350 date along the rural-urban gradient (Figure 8f).



351

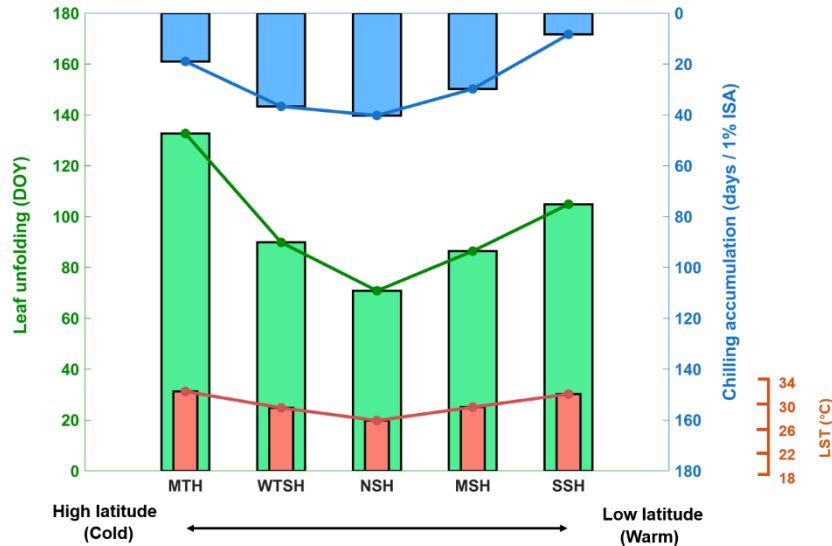
352 **Figure 8.** The response of leaf unfolding to LST along the rural-urban gradients in each  
 353 climate zone. a, climate zones with a linear relationship between leaf unfolding and LST. b-f, the  
 354 patterns of leaf unfolding, ISA, and LST in the plateau & semi-humid, cold temperate & humid,  
 355 tropical & humid, warm temperate & semi-arid and warm temperate and & arid, respectively. The  
 356 solid back line indicates the linear regression, and the dotted line indicates 50% ISA. **Notes:** PSH,  
 357 plateau & semi-humid zone; CTH, cold temperate & humid zone; TH, tropical & humid zone;  
 358 WTSA, warm temperate & semi-arid zone.

#### 359 4.4 The requirements of chilling accumulation

360 The leaf unfolding, LST, and chilling accumulation are north-south symmetrical regarding the  
 361 rural-urban ecosystem for the humid and extratropical zones (Figure 9). The leaf unfolding  
 362 requires less chilling accumulation and higher spring forcing LST for leaf unfolding in the  
 363 north and south latitudes. In general, the climate zones with later leaf unfolding dates  
 364 averagely experience less chilling accumulation days and need high spring forcing  
 365 temperatures. In contrast, the middle latitudes of China have the maximum days of chilling  
 366 accumulation and minimum requirement of forcing temperature for leaf unfolding. This is  
 367 possible because the frequency of daily air temperature below 0 °C during the dormancy  
 368 gradually increases from the NSH to the MTH, reducing chilling accumulation. Similarly, the  
 369 number of days with temperatures above 5 °C increases from the NSH to the SSH, causing a  
 370 decrease in chilling.

371 There are two explanations for the latitudinal symmetry of response between leaf unfolding  
 372 and LST, one according to the chilling requirement and the other based on the strategy for  
 373 self-protection. The plants need to experience a certain amount of chilling accumulation  
 374 before sprouting leaves in the spring (Murray et al., 1989). In contrast, this chilling  
 375 requirement is hardly met sooner during the dormancy in the north and south of China, as  
 376 mentioned above. As a result, the delayed time of leaf unfolding and seasonal temperature  
 377 warming cause the increase of LST. The other is that plants may develop a protective  
 378 mechanism related to heat requirement (Harrington et al., 2010) and photoperiod (Körner &  
 379 Basler, 2010) to reduce the risk of frost caused by climate fluctuation. Specifically, as the  
 380 extreme climatic events have significantly increased (Rahmstorf & Coumou, 2011), plants will

381 not start leaf unfolding until they accumulate a certain amount of heat or stably experience  
 382 enough long photoperiodic daytimes, which informs them that winter has passed. These  
 383 physical processes both take time, which results in the extension of dormancy release and  
 384 delay of spring phenology. Consequently, the seasonal temperature progressively warms as  
 385 time passes, and LST increases accordingly.



386 **Figure 9. The relationships among leaf unfolding, LST, and chilling requirement.** The green  
 387 bars are the average leaf unfolding time for each climate zone, and the red bars are the average  
 388 LST corresponding to the leaf unfolding time in each zone. The blue bars indicate the number of  
 389 accumulated chilling days per 1% ISA ( $0\text{ }^{\circ}\text{C} < T < 5\text{ }^{\circ}\text{C}$ ). The red bars are the average spring  
 390 LST.  
 391

## 392 5. Discussion

### 393 5.1 Regionalization and climatic peculiarities of urban phenology

394 Regionally, urbanization-induced land cover transformations could modify local  
 395 temperatures, hydrological regimes, and species composition that affect the spring phenology  
 396 consequently. The gradually increasing urbanization level and resultant UHI effects along the  
 397 rural-urban gradients cause the leaf to unfold earlier, with delayed trends at the highest  
 398 urbanization area (Figure 2). This is presumably because the UHI effects accelerate the  
 399 forcing unit accumulation and speed up plant growth, causing leaf unfolding to initiate earlier  
 400 between the urban and suburban. However, the relatively high temperature can lead to earlier  
 401 dormancy for the plants within the highest urbanization interval ( $\text{ISA} \geq 85\%$ ), so the chilling  
 402 accumulation requirements are thus unfulfilled for leaf unfolding (Zhang et al., 2022). Other  
 403 urbanization-induced factors could also alter the timing of spring phenology. For instance,  
 404 urban expansion could result in increased runoff and reduced groundwater (Pickett et al.,  
 405 2011) and hence influence the shifts of plants' life cycle. Besides, human preferences in  
 406 shaping urban landscapes and artificial management of irrigation and fertilization on  
 407 ornamental plants are likely to shift the spring phenology in the urban ecosystem. So, process-  
 408 based physiological models should be involved to provide explanatory suggestions and  
 409 technical support for future urban vegetation phenology studies, although it is beyond our  
 410 scope in this paper.

411 The phenological patterns in rural-urban ecosystems regionally vary in concert with climatic  
412 peculiarities. Many plants initiate leaf unfolding based on the necessity of temperature and  
413 humidity on which they depend (Menzel, 2002). We found no distinct linear correlations  
414 between spring phenology and urbanization (or LST) in the northmost, southmost, and arid  
415 zones, where temperatures are not mild or suffer rainfall deficit (Figure 3-4). The PSH, CTH,  
416 and TH have abundant precipitation, whereas their temperature is extremely cold or warm,  
417 making plants less sensitive to temperature variations in the leaf unfolding. For instance,  
418 spring temperature only slightly affects leafing time (Reich, 1995), whereas seasonal water  
419 status dominates tropical tree phenology (Borchert, 1998; Borchert et al., 2002). Additionally,  
420 low temperature and the resultant snow covers are the common climatic phenomena in the  
421 PSH and CTH zones. The snow occurrence and melting could influence the timing of the leaf  
422 unfolding by changing the temperature in many forms (Jönsson et al., 2010). Snow covers can  
423 keep soil temperature warm and inhibit soil frost penetration (Hirota et al., 2011) during winter  
424 to accelerate sprout for plants whose root temperature plays the most critical role in growth  
425 (Brouwer, 1962). The snow melting processes absorb heat, after which the air temperature is  
426 fixed above 0 °C, and plants begin their chilling accumulation to prepare leaf unfolding.  
427 Snow cover may also bring uncertainties for phenological measurements obtained by  
428 remotely sensed techniques (Yang et al., 2017). Moreover, the initiation of spring phenology is  
429 geographically symmetrical in the non-arid mid-latitudes. This geographical distribution is  
430 predicated upon climate according to their ability to adapt to the physical environment  
431 (Morecroft & Keith, 2009). Semi-arid and arid zones are exceptions that perform phenology  
432 differently because of water stress (e.g., water supply and demand) (Brown & Tanner, 1983;  
433 Flexas et al., 2006; Hsiao & Xu, 2000; Steinberg et al., 1990). For those zones, pre-season  
434 precipitation predominates in plant growth (Dai et al., 2004), and soil water availability  
435 governs the spring leaf unfolding (Los et al., 2001; Zhang et al., 2005). Thus, in arid regions,  
436 plants are likely to concentrate on unfolding leaves around the start of the rainy season  
437 (Chesson et al., 2004; Du et al., 2020).

438 The divergence of spring phenology dates across different climate zones is probably subject  
439 to varying degrees of chilling accumulation requirement during the dormancy caused by their  
440 climatic and geographical peculiarities. The insufficiency of chilling accumulation contributes  
441 to the delayed leaf unfolding dates at the high and low latitudes of China, where the climatic  
442 temperatures are below or above the threshold that needs for the chilling process. The  
443 interplay of winter cold and spring warm are key traits determining plants' response to the  
444 leaf's date unfolding to temperature (Kramer et al., 2017; Linkosalo et al., 2008; Luedeling et al.,  
445 2009). For boreal plants, the heat requirement is negatively correlated with chilling (Fu et al.,  
446 2013; Laube et al., 2014). Given that temperature warming and dormancy are negatively  
447 correlated, the delays of dormancy break and leaf unfolding are consequent upon the  
448 unfulfilled chilling requirements (Chuine et al., 2010). Once the chilling accumulation is  
449 fulfilled, actual leaf unfolding is a matter of concurrent temperature (Körner & Basler, 2010).  
450 Here, we only measured the average chilling accumulation of each pixel in the rural  
451 ecosystem during the dormancy to represent the general chilling amount for each climate  
452 zone. Appropriate chilling models would be necessary to measure the chilling accumulation  
453 to understand better the physical mechanism behind the spring leaf unfolding.

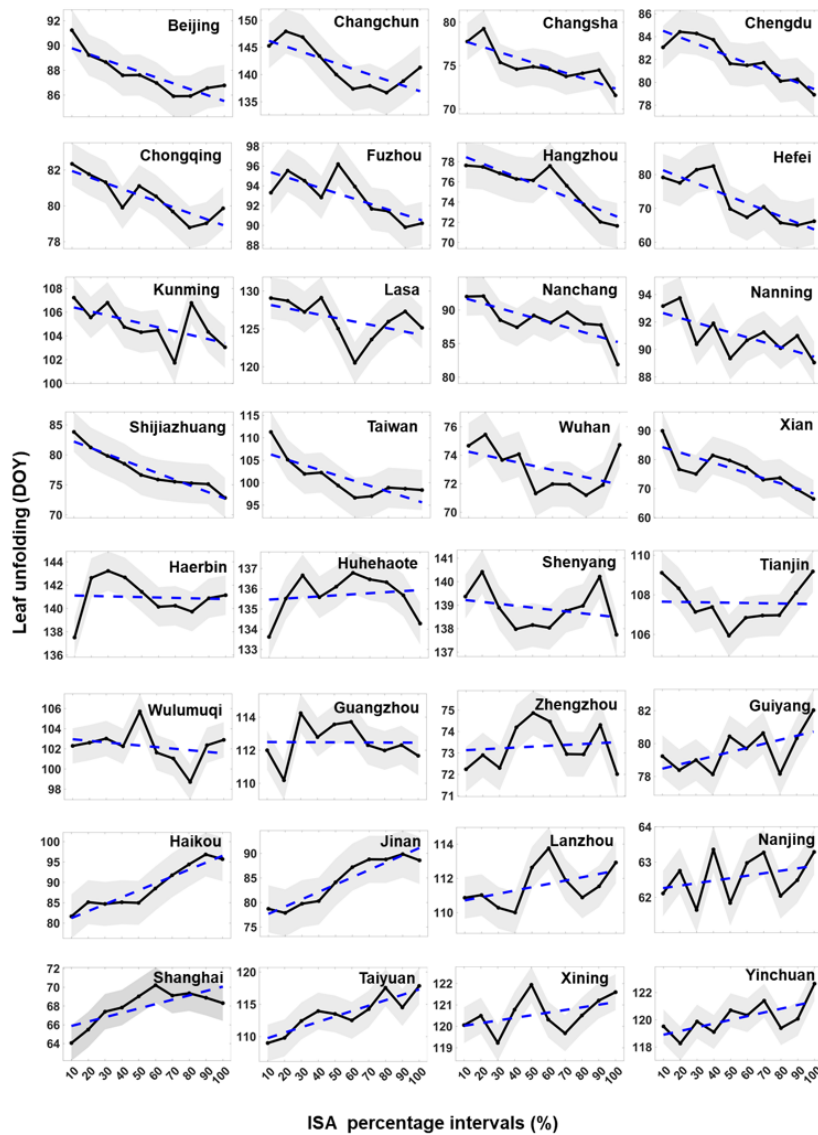
## 454 5.2 Plant adaptation in the context of urbanization and climate change

455 Plants can adapt to changes in their current environments through altering body functions or  
456 physiological behaviors (Bita & Gerats, 2013; Galvan-Ampudia et al., 2013; Měch &  
457 Prusinkiewicz, 1996). The response of leaf unfolding to urbanization is one example of how  
458 plants adjust to changing environments. We found that plants are finely tuned to the physical  
459 environment along the rural-urban gradients (Figure 7), perhaps because plants genetically  
460 possess the capabilities of adapting and evolving to deal with the changing environment  
461 (Bradshaw, 1965; Jump et al., 2009; Jump & Penuelas, 2005). As a result, those indigenous  
462 species preserved and survived during the urbanization process have already become  
463 invariable and adapted to the new environment due to their ability to tolerate physical  
464 conditions, even though the effects of urbanization on plants are complex. Over time, the  
465 plant species have progressively shifted their phenological time steps to ensure their living  
466 sustainability in urban habitats. Exotic plant species that humans planted in the rural-urban  
467 ecosystem could also influence the holistic spring phenology. As exotic species may exhibit  
468 different phenology from native plants in the natural ecosystem (Buyantuyev et al., 2012),  
469 there is a possibility that the spring phenology of exotic plants is also likely to differ from  
470 their indigenous counterparts in the rural-urban ecosystem. Additionally, based on the prior  
471 knowledge of humankind, many plants directly introduced by humans as substitutions for  
472 disappeared native species during the urbanization process can be believed to fit well in the  
473 complicated urban environment. Although the spring phenology status is stable under the  
474 effect of urbanization, some changes causing stress in plants are not detectable at the  
475 phenotype level (Gallego & Benavides, 2019). For instance, human management such as  
476 irrigation and fertilizer are in favor of their survival and growth as well.

477 As we have found that rural-urban plants respond differently to climatic peculiarities  
478 regarding leaf unfolding events, plants are believed to be capable of regulating corresponding  
479 behaviors to adapt to climate change. The globe has been warming significantly fast and  
480 comes along with frequently happened extreme climatic events (AghaKouchak et al., 2014;  
481 Rahmstorf & Coumou, 2011). Many plant species are unable to adapt to climatic environments  
482 that may negatively influence their survival in new areas (Bonte et al., 2012), resulting in a  
483 potential increase of extinction risks (Thomas et al., 2004). The adaptation in the response of  
484 plants to climate change is thus essential for their survival (Ahuja et al., 2010; Corlett et al.,  
485 2013; McDowell et al., 2008). Many plants have evolved to adapt to climate change and  
486 extreme living conditions, aided by natural selection. For instance, species with a lower  
487 chilling requirement may profit from warming winters (Laube et al., 2014). The species that  
488 survived adaptively may share similar phenotypic plasticity of traits such as rehabilitation and  
489 acclimatization ability to self-regulate their ambient environment (Matesanz & Gianoli, 2014;  
490 Van Kleunen & Fischer, 2005). These adaptive traits determined by genes are necessary to  
491 cope with abiotic or biotic stress for plant tolerance and resistance (Van Schaik et al., 1993),  
492 indicating that plants adapt to global warming in the direction based on their physiological  
493 constraints and will eventually become an indispensable part to the new ecosystem (Root et  
494 al., 2003).

495 **5.3 Uncertainties**

496 We found that phenological leaf unfolding is diverse on the city-scale regionality (Figure 10).  
 497 In general, 50% of China’s major cities experience advanced dates of leaf unfolding along the  
 498 rural-urban gradients. In comparison, 30% of cities show delayed trends of leaf unfolding,  
 499 while the leaf unfolding is irrelevant to the urbanization for the remaining cities. Logically  
 500 and technically speaking, the climatic peculiarities within a city is much likely to be  
 501 homogeneous in terms of temperature, humidity, vegetation types, and so forth at such a  
 502 relatively small local scale. We did not find any spatial patterns among the cities to interpret  
 503 whether advanced or delayed trends of leaf unfolding are geospatially correlated, and those  
 504 trends also fluctuate extremely along the rural-urban gradients. The dissimilitude, as a result,  
 505 can be possibly ascribed to the accuracy of detecting phenological metrics through remote  
 506 sensing (Liu & Zhang, 2020).



507

508 **Figure 10.** The correlation between ISA and leaf unfolding on the city scales. The dotted blue  
 509 line indicates the linear regression, and the grey area indicates one standard deviation on either  
 510 side of the mean.

511 The coarse spatial resolution presents substantial challenges for studies of urban phenology  
512 (Melaas et al., 2016). Analyzing the spring phenology along the rural-urban manner could be  
513 influenced by the resolution of remotely sensed data. The coarse resolution could impact the  
514 significance level of trends in statistical analysis. Currently, the remotely sensed approach to  
515 determining the time of phenological metrics is predicated on observing surface greenness  
516 (Zhang et al., 2017). The nominal onset of greenness often includes spectral signals of many  
517 other objects, such as soil, buildings, and roads in the rural-urban systems. For instance, the  
518 satellite-derived signals of urban areas (ISA percentage  $\geq 85\%$ ) include less information about  
519 plants, and the rural areas (ISA percentage  $\leq 5\%$ ) contain signals more about crop and soil  
520 background. Additionally, although the cloudy conditions may hamper the phenological  
521 retrieval by satellites as well, the six-year average observations we used can substantially  
522 reduce its effects.

523 To date, the rural-urban differences of phenology have been confined to remote sensing,  
524 which can only reflect ecosystem-level signals of greenness (Reed et al., 1994). It is hard to  
525 link an individual leaf to the regional scale (Morissette et al., 2009) because of the diverse plant  
526 species along the rural-urban gradients. Comparing the phenological difference between the  
527 rural and urban with different plant types is likely to generate inaccuracies and uncertainties,  
528 and attributing the earlier initiation of leaf unfolding in the urban area to the UHI effects  
529 could thus provide unscientific information for climate change observations. Nevertheless, we  
530 can also consider crops as an indispensable part of the rural-urban ecosystem. Such ideas are  
531 based on the fact that the rural-urban region extensively covers a spatial area, implying it  
532 contains more than one species. The population observed in a small area is not sufficient and  
533 representative to generally illuminate the climate effects on plants. Plant responses to  
534 warming differ among species (Yu et al., 2010), and the variation of leaf unfolding can be  
535 more than two weeks within a 500 m area, even though plants belong to the same species  
536 (Fisher et al., 2006). Also, there is no need for precise interpretations of changing plant species  
537 at the rural-urban community scale, as all living organisms coexist in this ecosystem and self-  
538 or mutual regulate, making them a whole. So, even though the coarse resolution satellite-  
539 derived measurements fail to capture the phenological events for one particular species (Liang  
540 et al., 2011; Schwartz et al., 2002), they monitor the phenology of all species in a community  
541 (Cleland et al., 2007), which is universally important for global climate change.

542 A lack of in-situ phenological data for verification limits the application of satellite-derived  
543 phenological measurements (Badeck et al., 2004). Phenological observations across taxa  
544 should be integrated and synthesized together to discuss further how one specific species, or a  
545 commonly mixed vegetation landscape (e.g., the combination of wood and herbaceous  
546 plants), responds to urbanization. This cooperative combination poses great challenges to the  
547 spatial resolution for satellite imagery because the unit of satellite-derived measurements  
548 consists of many individual species, which initiates leaf unfolding at different times. Also,  
549 resampling for datasets from different resources will incur aliasing errors. Therefore, fine-  
550 resolution sensors such as Landsat are highly recommended for phenological monitoring on  
551 the rural-urban scale because it is well-synchronized with photographs taken on the ground.

552 **6. Conclusion**

553 Projected future rapid global climate change accompanied by intricately human-involved  
554 physical environment could dramatically influence the phenological events for plants. Our  
555 study is the first attempt at a national scale to study the spring phenology response to  
556 urbanization in the context of different climate zones, which has engendered good qualitative  
557 arguments in favor of a climate-change effect on phenology. Our results show that spring leaf  
558 unfolding responds divergently to the temperature caused by the UHI effects on the different  
559 levels of urbanization. Regionally, leaf unfolding and urbanization are highly correlated in the  
560 mid-latitudes with moderate climate (temperature and humidity), and this correlation  
561 decreases to the low and high latitudes, respectively. In the rural-urban ecosystem, leaf  
562 unfolding time shows north-south symmetrical patterns according to the climate peculiarities  
563 in China, rather than the higher the temperature causes the earlier initiation of spring  
564 phenology. The requirement of chilling accumulation is the primary driver behind these  
565 phenomena, accompanied by plants' adaption capability that makes it possible for them to  
566 shift their phenological time to cope with climate change correspondingly. In this study, the  
567 advances in the phenology of urban ecosystems can improve the understanding of climate  
568 warming-plant adaptation connection. In the context of climate change, the development and  
569 physiology of plants potentially can be reshaped to acclimate to the different living  
570 environments of the planet, from tropical to temperature zone, through the rural or urban area.

571 Exploring the plant responses to urbanization is helpful for us to understand to what extent  
572 they can adapt to a complex environment where changes in temperatures and human activities  
573 happen all the time. Probing into the climatic peculiarities about the rural-urban ecosystem  
574 prepares prior knowledge for us to forecast global climate change in the future.  
575 Understanding the influence of plants in response to climate change is therefore critical for  
576 detecting global warming trends. By incorporating climatic peculiarities in the spring  
577 phenology of rural-urban ecosystems, future phenological models could be more robust to  
578 explain the biological reactions of plants in response to climate change and other physical  
579 regimes. Further efforts such as integrating multiple techniques and synthesizing across  
580 different scales are required to sufficiently use observations based on the present and past to  
581 extrapolate and model the possible interactions and responses between climate and biospheric  
582 systems under different future scenarios.

583 **References**

584

- 585 AghaKouchak, Cheng, Mazdiyasni, & Farahmand. (2014). Global warming and changes in risk of  
586 concurrent climate extremes: Insights from the 2014 California drought. *41*(24), 8847-8852.
- 587 Ahuja, de Vos, Bones, & Hall. (2010). Plant molecular stress responses face climate change. *15*(12),  
588 664-674.
- 589 Allen, Barros, Broome, Cramer, Christ, Church, . . . Dubash. (2014). IPCC fifth assessment synthesis  
590 report-climate change 2014 synthesis report.
- 591 Badeck, Bondeau, Böttcher, Doktor, Lucht, Schaber, & Sitch. (2004). Responses of spring phenology  
592 to climate change. *162*(2), 295-309.
- 593 Bakkenes, Alkemade, Ihle, Leemans, & Latour. (2002). Assessing effects of forecasted climate change  
594 on the diversity and distribution of European higher plants for 2050. *8*(4), 390-407.
- 595 Benali, Carvalho, Nunes, Carvalhais, & Santos. (2012). Estimating air surface temperature in Portugal  
596 using MODIS LST data. *124*, 108-121.
- 597 Bita, & Gerats. (2013). Plant tolerance to high temperature in a changing environment: scientific  
598 fundamentals and production of heat stress-tolerant crops. *4*, 273.
- 599 Bonte, Van Dyck, Bullock, Coulon, Delgado, Gibbs, . . . Saastamoinen. (2012). Costs of dispersal.  
600 *87*(2), 290-312.
- 601 Borchert. (1998). Responses of tropical trees to rainfall seasonality and its long-term changes. In  
602 *Potential impacts of climate change on tropical forest ecosystems* (pp. 241-253): Springer.
- 603 Borchert, Rivera, & Hagnauer. (2002). Modification of Vegetative Phenology in a Tropical Semi -  
604 deciduous Forest by Abnormal Drought and Rain 1. *34*(1), 27-39.
- 605 Bradshaw. (1965). Evolutionary significance of phenotypic plasticity in plants. In *Advances in genetics*  
606 (Vol. 13, pp. 115-155): Elsevier.
- 607 Brouwer. (1962). Distribution of dry matter in the plant. *10*(5), 361-376.
- 608 Brown, & Tanner. (1983). Alfalfa stem and leaf growth during water stress 1. *75*(5), 799-805.
- 609 Buyantuyev, Wu, & Planning. (2012). Urbanization diversifies land surface phenology in arid  
610 environments: interactions among vegetation, climatic variation, and land use pattern in the  
611 Phoenix metropolitan region, USA. *105*(1-2), 149-159.
- 612 Chesson, Gebauer, Schwinning, Huntly, Wiegand, Ernest, . . . Weltzin. (2004). Resource pulses,  
613 species interactions, and diversity maintenance in arid and semi-arid environments. *141*(2),  
614 236-253.
- 615 Chuine, Morin, & Bugmann. (2010). Warming, photoperiods, and tree phenology. *329*(5989), 277-278.
- 616 Cleland, Chuine, Menzel, Mooney, Schwartz, & evolution. (2007). Shifting plant phenology in  
617 response to global change. *22*(7), 357-365.
- 618 Corlett, Westcott, & evolution. (2013). Will plant movements keep up with climate change? , *28*(8),  
619 482-488.
- 620 Coumou, & Rahmstorf. (2012). A decade of weather extremes. *2*(7), 491-496.
- 621 Coville. (1920). The influence of cold in stimulating the growth of plants. *20*(2), 151-160.
- 622 d'Amour, Reitsma, Baiocchi, Barthel, Güneralp, Erb, . . . Seto. (2017). Future urban land expansion  
623 and implications for global croplands. *114*(34), 8939-8944.
- 624 Dai, Trenberth, & Qian. (2004). A global dataset of Palmer Drought Severity Index for 1870–2002:

625 Relationship with soil moisture and effects of surface warming. *5*(6), 1117-1130.

626 De Beurs, & Henebry. (2004). Land surface phenology, climatic variation, and institutional change:  
627 Analyzing agricultural land cover change in Kazakhstan. *89*(4), 497-509.

628 Diffenbaugh, Singh, Mankin, Horton, Swain, Touma, . . . Tsiang. (2017). Quantifying the influence of  
629 global warming on unprecedented extreme climate events. *114*(19), 4881-4886.

630 Du, Li, He, Chen, Lin, & Zhu. (2020). Daily minimum temperature and precipitation control on spring  
631 phenology in arid - mountain ecosystems in China. *40*(5), 2568-2579.

632 Field, & Barros. (2014). *Climate change 2014—Impacts, adaptation and vulnerability: Regional  
633 aspects*: Cambridge University Press.

634 Fisher, Mustard, & Vadeboncoeur. (2006). Green leaf phenology at Landsat resolution: Scaling from  
635 the field to the satellite. *100*(2), 265-279.

636 Flexas, Bota, Galmes, Medrano, & Ribas - Carbó. (2006). Keeping a positive carbon balance under  
637 adverse conditions: responses of photosynthesis and respiration to water stress. *127*(3), 343-  
638 352.

639 Foley, Prentice, Ramankutty, Levis, Pollard, Sitch, & Haxeltine. (1996). An integrated biosphere  
640 model of land surface processes, terrestrial carbon balance, and vegetation dynamics. *10*(4),  
641 603-628.

642 Friedl, Gray, Melaas, Richardson, Hufkens, Keenan, . . . O’Keefe. (2014). A tale of two springs: using  
643 recent climate anomalies to characterize the sensitivity of temperate forest phenology to  
644 climate change. *9*(5), 054006.

645 Fu, Campioli, Deckmyn, Janssens, & Meteorology. (2013). Sensitivity of leaf unfolding to  
646 experimental warming in three temperate tree species. *181*, 125-132.

647 Gallego, & Benavides. (2019). Cadmium-induced oxidative and nitrosative stress in plants. In  
648 *Cadmium Toxicity and Tolerance in Plants* (pp. 233-274): Elsevier.

649 Galvan-Ampudia, Julkowska, Darwish, Gandullo, Korver, Brunoud, . . . Testerink. (2013).  
650 Halotropism is a response of plant roots to avoid a saline environment. *23*(20), 2044-2050.

651 Gao, & O’Neill. (2020). Mapping global urban land for the 21st century with data-driven simulations  
652 and Shared Socioeconomic Pathways. *11*(1), 1-12.

653 Gong, Li, Wang, Bai, Chen, Hu, . . . Zhang. (2020). Annual maps of global artificial impervious area  
654 (GAIA) between 1985 and 2018. *236*, 111510.

655 Gorelick, Hancher, Dixon, Ilyushchenko, Thau, & Moore. (2017). Google Earth Engine: Planetary-  
656 scale geospatial analysis for everyone. *202*, 18-27.

657 Graham, Riordan, Yuen, Estrin, & Rundel. (2010). Public Internet - connected cameras used as a cross  
658 - continental ground - based plant phenology monitoring system. *16*(11), 3014-3023.

659 Griggs, & Noguer. (2002). Climate change 2001: the scientific basis. Contribution of working group I  
660 to the third assessment report of the intergovernmental panel on climate change. *57*(8), 267-  
661 269.

662 Gu, Post, Baldocchi, Black, Verma, Vesala, & Wofsy. (2003). Phenology of vegetation photosynthesis.  
663 In *Phenology: An integrative environmental science* (pp. 467-485): Springer.

664 Harrington, Gould, Clair, & Management. (2010). Modeling the effects of winter environment on

665 dormancy release of Douglas-fir. *259*(4), 798-808.

666 He, Yang, Tang, Lu, Qin, Chen, & Li. (2020). The first high-resolution meteorological forcing dataset  
667 for land process studies over China. *7*(1), 1-11.

668 Hirota, Usuki, Hayashi, Nemoto, Iwata, Yanai, . . . Change. (2011). Soil frost control: agricultural  
669 adaptation to climate variability in a cold region of Japan. *16*(7), 791-802.

670 Hsiao, & Xu. (2000). Sensitivity of growth of roots versus leaves to water stress: biophysical analysis  
671 and relation to water transport. *51*(350), 1595-1616.

672 Hufkens, Basler, Milliman, Melaas, Richardson, & Evolution. (2018). An integrated phenology  
673 modelling framework in R. *9*(5), 1276-1285.

674 Imhoff, Zhang, Wolfe, & Bounoua. (2010). Remote sensing of the urban heat island effect across  
675 biomes in the continental USA. *114*(3), 504-513.

676 Jia, Zhao, Zhang, Liu, Henebry, & Liu. (2021). Urbanization imprint on land surface phenology: The  
677 urban–rural gradient analysis for Chinese cities. *27*(12), 2895-2904.

678 Jin, Dickinson, & Zhang. (2005). The footprint of urban areas on global climate as characterized by  
679 MODIS. *18*(10), 1551-1565.

680 Jönsson, Eklundh, Hellström, & Barring. (2010). Annual changes in MODIS vegetation indices of  
681 Swedish coniferous forests in relation to snow dynamics and tree phenology. *114*(11), 2719-  
682 2730.

683 Jump, Marchant, & Peñuelas. (2009). Environmental change and the option value of genetic diversity.  
684 *14*(1), 51-58.

685 Jump, & Penuelas. (2005). Running to stand still: adaptation and the response of plants to rapid climate  
686 change. *8*(9), 1010-1020.

687 Keenan, Darby, Felts, Sonntag, Friedl, Hufkens, . . . Toomey. (2014). Tracking forest phenology and  
688 seasonal physiology using digital repeat photography: a critical assessment. *24*(6), 1478-1489.

689 Körner, & Basler. (2010). Phenology under global warming. *327*(5972), 1461-1462.

690 Kramer, Ducouso, Gömöry, Hansen, Ionita, Liesebach, . . . Meteorology. (2017). Chilling and forcing  
691 requirements for foliage bud burst of European beech (*Fagus sylvatica* L.) differ between  
692 provenances and are phenotypically plastic. *234*, 172-181.

693 Landsberg. (1981). *The urban climate*: Academic press.

694 Latif, & Keenlyside. (2009). El Niño/Southern Oscillation response to global warming. *106*(49),  
695 20578-20583.

696 Laube, Sparks, Estrella, Höfler, Ankerst, & Menzel. (2014). Chilling outweighs photoperiod in  
697 preventing precocious spring development. *20*(1), 170-182.

698 Li, Gong, & Liang. (2015). A 30-year (1984–2013) record of annual urban dynamics of Beijing City  
699 derived from Landsat data. *166*, 78-90.

700 Li, Zhou, Meng, Asrar, Sapkota, & Coates. (2019). Characterizing the relationship between satellite  
701 phenology and pollen season: a case study of birch. *222*, 267-274.

702 Liang, Schwartz, & Fei. (2011). Validating satellite phenology through intensive ground observation  
703 and landscape scaling in a mixed seasonal forest. *115*(1), 143-157.

704 Linkosalo, Lappalainen, & Hari. (2008). A comparison of phenological models of leaf bud burst and  
705 flowering of boreal trees using independent observations. *28*(12), 1873-1882.

706 Liu, & Zhang. (2020). Effects of temperature variability and extremes on spring phenology across the  
707 contiguous United States from 1982 to 2016. *10*(1), 1-14.

708 Long, Liu, Wu, & Dong. (2009). Spatio-temporal dynamic patterns of farmland and rural settlements in

709 Su–Xi–Chang region: Implications for building a new countryside in coastal China. *26*(2),  
710 322-333.

711 Los, Collatz, Bounoua, Sellers, & Tucker. (2001). Global interannual variations in sea surface  
712 temperature and land surface vegetation, air temperature, and precipitation. *14*(7), 1535-1549.

713 Luedeling, Zhang, McGranahan, Leslie, & Meteorology. (2009). Validation of winter chill models  
714 using historic records of walnut phenology. *149*(11), 1854-1864.

715 Masson-Delmotte, Zhai, Pörtner, Roberts, Skea, Shukla, . . . Pidcock. (2018). Global warming of 1.5 C.  
716 *1*(5).

717 Matesanz, & Gianoli. (2014). Global change and the evolution of phenotypic plasticity in plants.

718 McDowell, Pockman, Allen, Breshears, Cobb, Kolb, . . . Williams. (2008). Mechanisms of plant  
719 survival and mortality during drought: why do some plants survive while others succumb to  
720 drought? , *178*(4), 719-739.

721 Měch, & Prusinkiewicz. (1996). *Visual models of plants interacting with their environment*. Paper  
722 presented at the Proceedings of the 23rd annual conference on Computer graphics and  
723 interactive techniques.

724 Melaas, Wang, Miller, & Friedl. (2016). Interactions between urban vegetation and surface urban heat  
725 islands: a case study in the Boston metropolitan region. *11*(5), 054020.

726 Meng, Mao, Zhou, Richardson, Lee, Thornton, . . . Shi. (2020). Urban warming advances spring  
727 phenology but reduces the response of phenology to temperature in the conterminous United  
728 States. *117*(8), 4228-4233.

729 Menzel. (2002). Phenology: its importance to the global change community. *Climatic change*, *54*(4),  
730 379.

731 Menzel, Sparks, Estrella, Koch, Aasa, Ahas, . . . Briede. (2006). European phenological response to  
732 climate change matches the warming pattern. *12*(10), 1969-1976.

733 Morecroft, & Keith. (2009). Plant ecology as an indicator of climate and global change. In *Climate*  
734 *Change* (pp. 297-305): Elsevier.

735 Morissette, Richardson, Knapp, Fisher, Graham, Abatzoglou, . . . Environment. (2009). Tracking the  
736 rhythm of the seasons in the face of global change: phenological research in the 21st century.  
737 *7*(5), 253-260.

738 Murray, Cannell, & Smith. (1989). Date of budburst of fifteen tree species in Britain following climatic  
739 warming. 693-700.

740 Myneni, Keeling, Tucker, Asrar, & Nemani. (1997). Increased plant growth in the northern high  
741 latitudes from 1981 to 1991. *386*(6626), 698-702.

742 Ogunbode, Doran, & Böhm. (2020). Exposure to the IPCC special report on 1.5 C global warming is  
743 linked to perceived threat and increased concern about climate change. *158*(3), 361-375.

744 Parmesan, & Yohe. (2003). A globally coherent fingerprint of climate change impacts across natural  
745 systems. *421*(6918), 37-42.

746 Peñuelas, & Filella. (2001). Responses to a warming world. *294*(5543), 793-795.

747 Pettorelli, Vik, Mysterud, Gaillard, Tucker, Stenseth, & evolution. (2005). Using the satellite-derived  
748 NDVI to assess ecological responses to environmental change. *20*(9), 503-510.

749 Piao, Liu, Chen, Janssens, Fu, Dai, . . . Zhu. (2019). Plant phenology and global climate change:  
750 Current progresses and challenges. *25*(6), 1922-1940.

751 Piao, Liu, Wang, Peng, Ciais, Huang, . . . Janssens. (2017). Weakening temperature control on the  
752 interannual variations of spring carbon uptake across northern lands. *7*(5), 359-363.

753 Pickett, Cadenasso, Grove, Boone, Groffman, Irwin, . . . Nilon. (2011). Urban ecological systems:  
754 Scientific foundations and a decade of progress. *92*(3), 331-362.

755 Rahmstorf, & Coumou. (2011). Increase of extreme events in a warming world. *108*(44), 17905-17909.

756 Reed, Brown, VanderZee, Loveland, Merchant, & Ohlen. (1994). Measuring phenological variability  
757 from satellite imagery. *5*(5), 703-714.

758 Reich. (1995). Phenology of tropical forests: patterns, causes, and consequences. *73*(2), 164-174.

759 Richardson, Braswell, Hollinger, Jenkins, & Ollinger. (2009). Near - surface remote sensing of spatial  
760 and temporal variation in canopy phenology. *19*(6), 1417-1428.

761 Root, Price, Hall, Schneider, Rosenzweig, & Pounds. (2003). Fingerprints of global warming on wild  
762 animals and plants. *421*(6918), 57-60.

763 Schwartz, Ahas, & Aasa. (2006). Onset of spring starting earlier across the Northern Hemisphere.  
764 *12*(2), 343-351.

765 Schwartz, Reed, & White. (2002). Assessing satellite - derived start - of - season measures in the  
766 conterminous USA. *22*(14), 1793-1805.

767 Solecki, Rosenzweig, Parshall, Pope, Clark, Cox, & Wiencke. (2005). Mitigation of the heat island  
768 effect in urban New Jersey. *6*(1), 39-49.

769 Steinberg, Miller, & McFarland. (1990). Dry matter partitioning and vegetative growth of young peach  
770 trees under water stress. *17*(1), 23-36.

771 Thomas, Cameron, Green, Bakkenes, Beaumont, Collingham, . . . Hannah. (2004). Extinction risk from  
772 climate change. *427*(6970), 145-148.

773 Trenberth, Fasullo, & Shepherd. (2015). Attribution of climate extreme events. *5*(8), 725-730.

774 Van Kleunen, & Fischer. (2005). Constraints on the evolution of adaptive phenotypic plasticity in  
775 plants. *166*(1), 49-60.

776 Van Schaik, Terborgh, Wright, & Systematics. (1993). The phenology of tropical forests: adaptive  
777 significance and consequences for primary consumers. *24*(1), 353-377.

778 Walther, Post, Convey, Menzel, Parmesan, Beebee, . . . Bairlein. (2002). Ecological responses to recent  
779 climate change. *416*(6879), 389-395.

780 Watson. (1996). *Impacts, Adaptations and Mitigation of Climate Change: Scientific-technical*  
781 *Analyses; Contribution of Working Group II to the Second Assessment Report of the*  
782 *Intergovernmental Panel on Climate Change*: University Press.

783 Way, Montgomery, & environment. (2015). Photoperiod constraints on tree phenology, performance  
784 and migration in a warming world. *38*(9), 1725-1736.

785 Woodward, & Woodward. (1987). *Climate and plant distribution*: Cambridge University Press.

786 Xu. (2010). Analysis of impervious surface and its impact on urban heat environment using the  
787 normalized difference impervious surface index (NDISI). *76*(5), 557-565.

788 Xu, Ramanathan, & Victor. (2018). Global warming will happen faster than we think. In: Nature  
789 Publishing Group.

790 Yang, & He. (2019). China meteorological forcing dataset (1979–2018). *National Tibetan Plateau*  
791 *Data Center, 10*.

792 Yang, He, Shishov, Tychkov, Vaganov, Rossi, . . . Griebinger. (2017). New perspective on spring  
793 vegetation phenology and global climate change based on Tibetan Plateau tree-ring data.  
794 *114*(27), 6966-6971.

795 Yang, Hou, & Chen. (2011). Observed surface warming induced by urbanization in east China.  
796 *116(D14)*.

797 Yu, Luedeling, & Xu. (2010). Winter and spring warming result in delayed spring phenology on the  
798 Tibetan Plateau. *107(51)*, 22151-22156.

799 Zhang, Friedl, Schaaf, Strahler, Hodges, Gao, . . . Huete. (2003). Monitoring vegetation phenology  
800 using MODIS. *84(3)*, 471-475.

801 Zhang, Friedl, Schaaf, Strahler, & Liu. (2005). Monitoring the response of vegetation phenology to  
802 precipitation in Africa by coupling MODIS and TRMM instruments. *110(D12)*.

803 Zhang, Friedl, Schaaf, Strahler, & Schneider. (2004). The footprint of urban climates on vegetation  
804 phenology. *31(12)*.

805 Zhang, Jayavelu, Liu, Friedl, Henebry, Liu, . . . Meteorology. (2018). Evaluation of land surface  
806 phenology from VIIRS data using time series of PhenoCam imagery. *256*, 137-149.

807 Zhang, Liu, Liu, Jayavelu, Wang, Moon, . . . Schaaf. (2018). Generation and evaluation of the VIIRS  
808 land surface phenology product. *Remote Sensing of Environment*, *216*, 212-229.

809 Zhang, Wang, Gao, Liu, Schaaf, Friedl, . . . Liu. (2017). Exploration of scaling effects on coarse  
810 resolution land surface phenology. *190*, 318-330.

811 Zhang, Yin, Li, Niu, Wang, Cao, . . . Yu. (2022). The divergent response of vegetation phenology to  
812 urbanization: A case study of Beijing city, China. *803*, 150079.

813 Zhao, Liu, & Zhou. (2016). Prevalent vegetation growth enhancement in urban environment. *113(22)*,  
814 6313-6318.

815 Zhou, Zhao, Zhang, & Liu. (2016). Remotely sensed assessment of urbanization effects on vegetation  
816 phenology in China's 32 major cities. *176*, 272-281.

817