# Urban warming advances spring phenology but reduces the response of phenology to temperature in the conterminous United States

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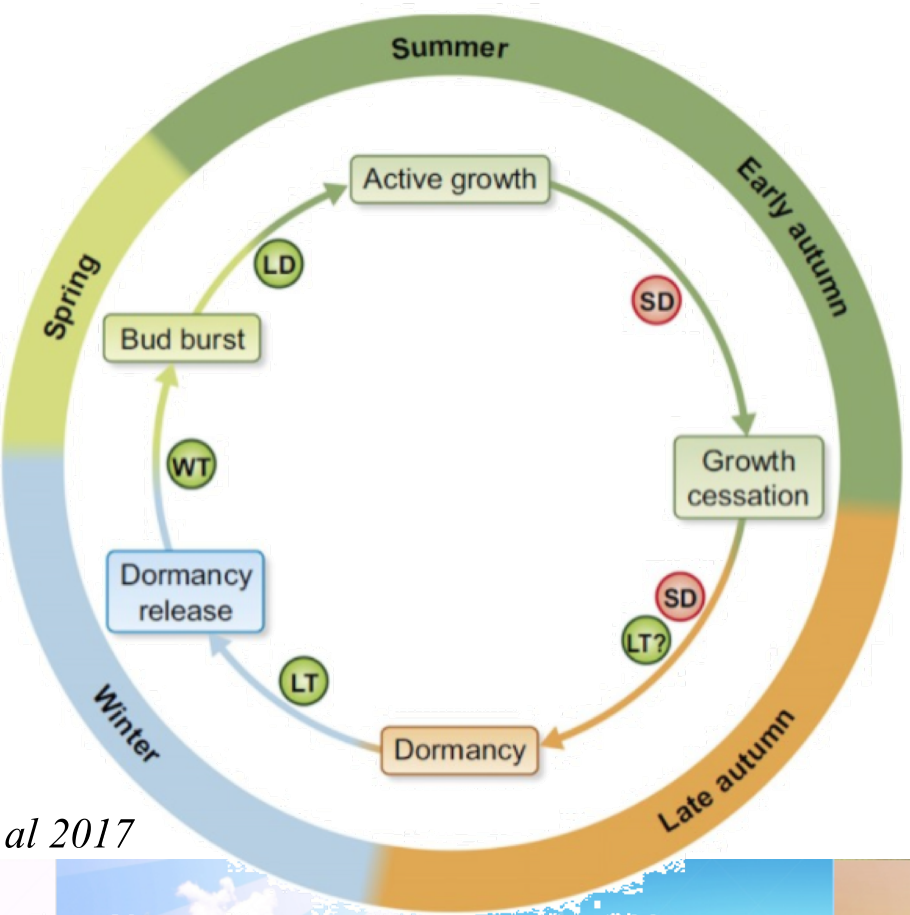
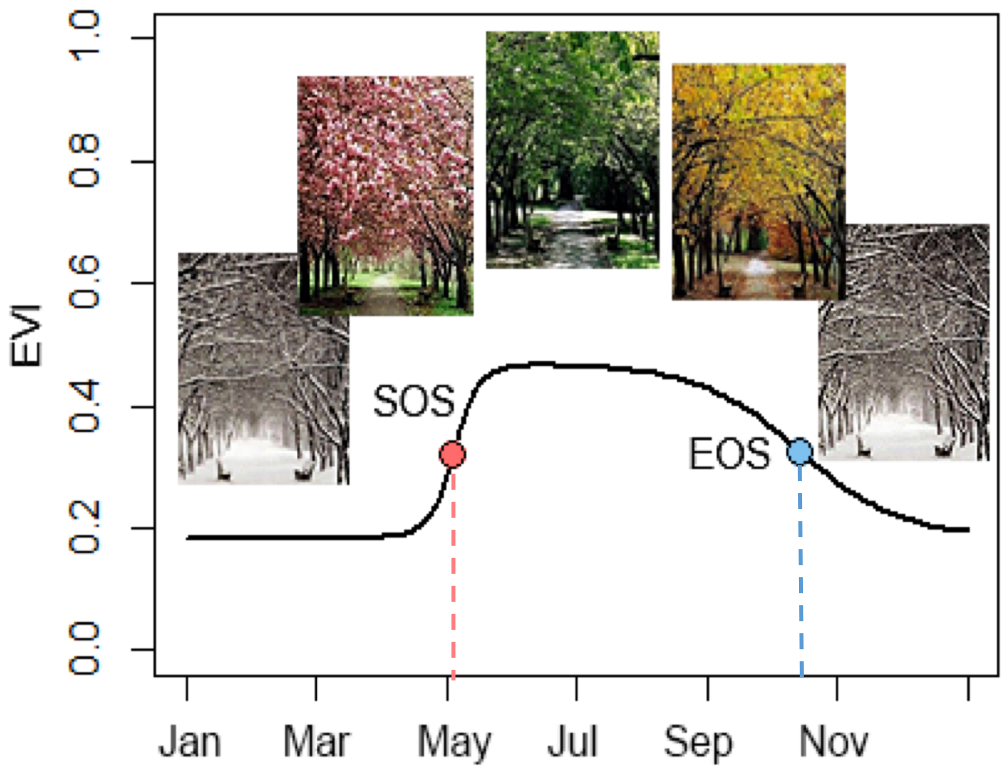
# Phenology is the timing of plant’s life cycle events

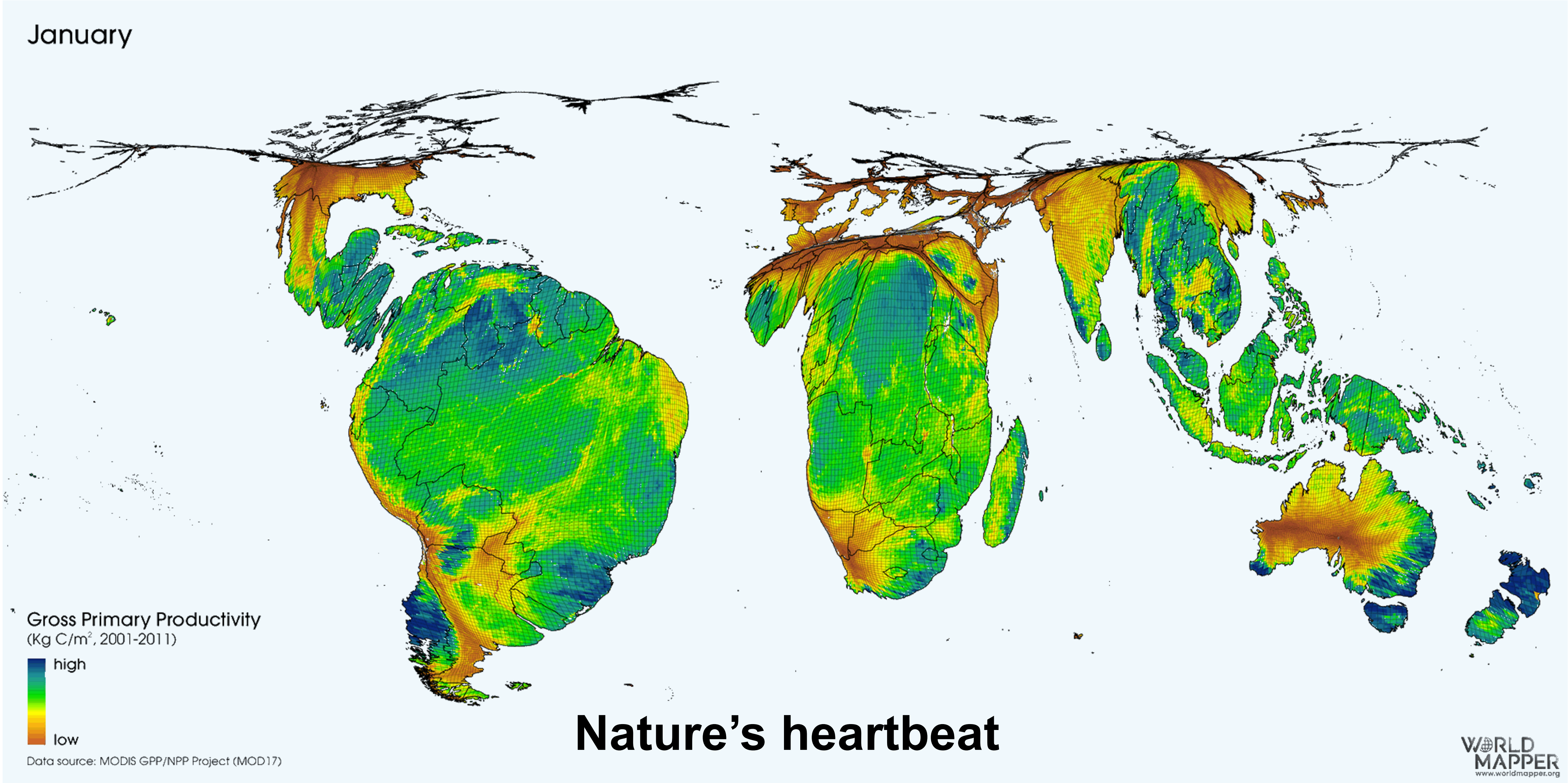



*Source: Singh et al 2017*




**Satellite derived phenology indicator: start of season (SOS)**

# Phenology as a proxy for land-atmosphere interaction




https://worldmapper.org/natures-heartbeat/



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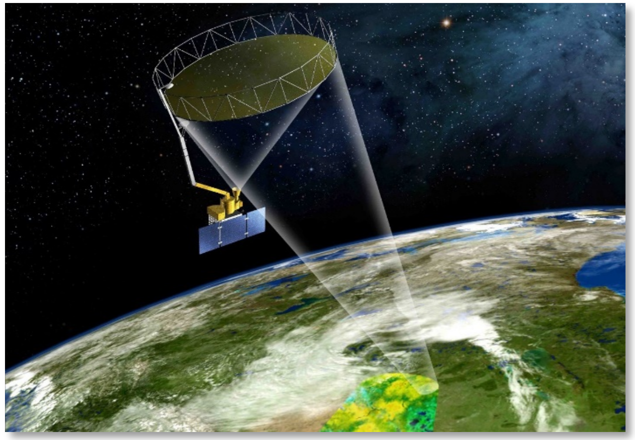
# Earlier spring green-up driven by warming condition

Warming experiment

Satellite observation



Ground observation

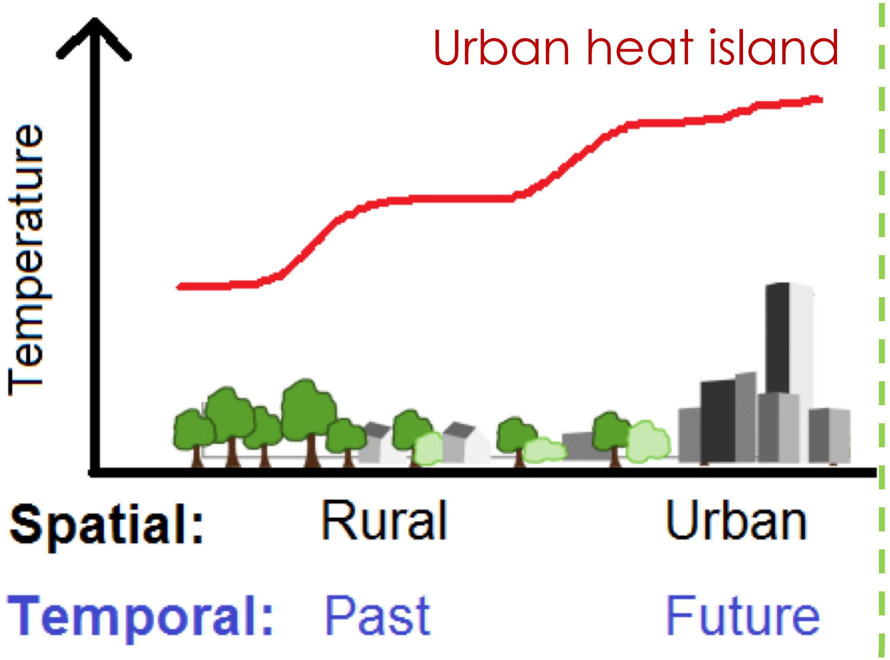
**Earlier start of season and extended growing season**

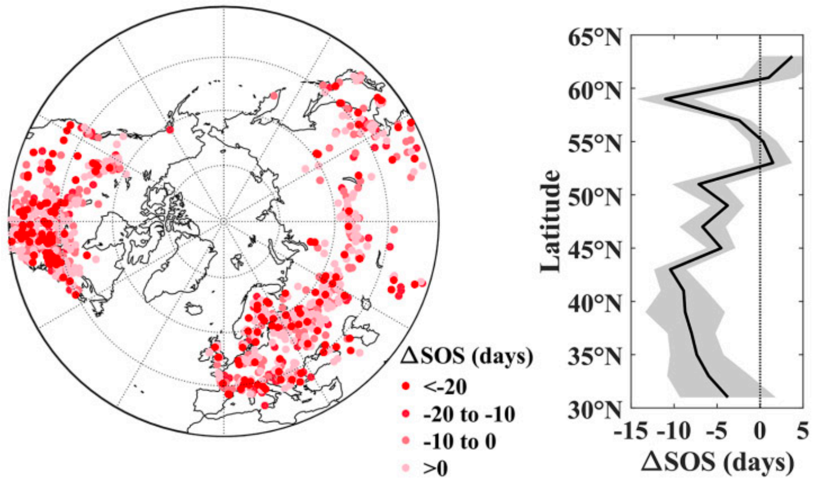
**Limitations:**

- Relatively short observational periods in experimental observations;
- The use of saplings or twigs instead of mature trees;
- Uncertainties on future phenological changes under warming.

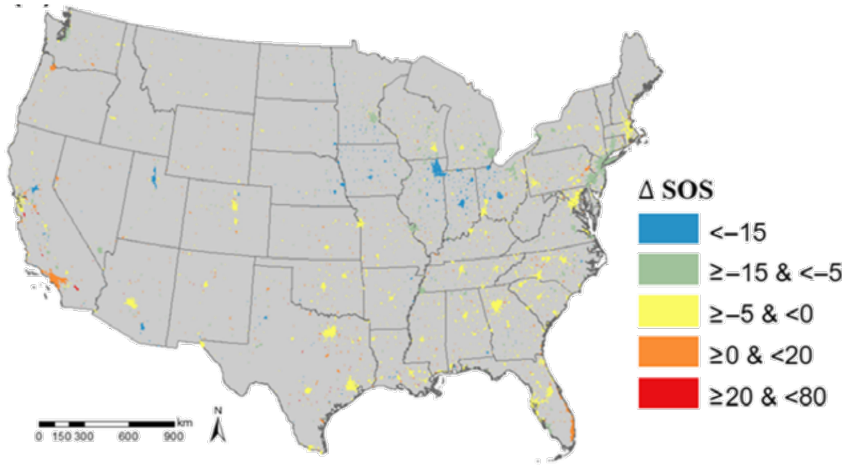
# "Urban laboratory" for phenology studies

Space-time substitution



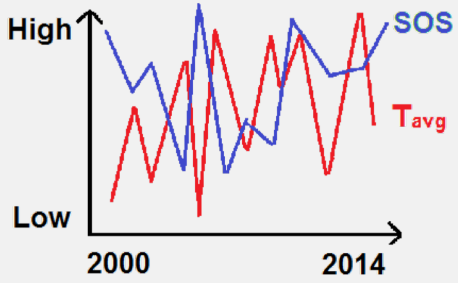

*Wang, et al. Urban−rural gradients reveal joint control of elevated $CO_2$ and temperature on extended photosynthetic seasons. 2019. Nature Ecology & Evolution.*




*Li, et al. Response of vegetation phenology to urbanization in the conterminous United States. 2016. Global Change Biology.*

**Earlier start of season (SOS) in urban areas verses rural areas**

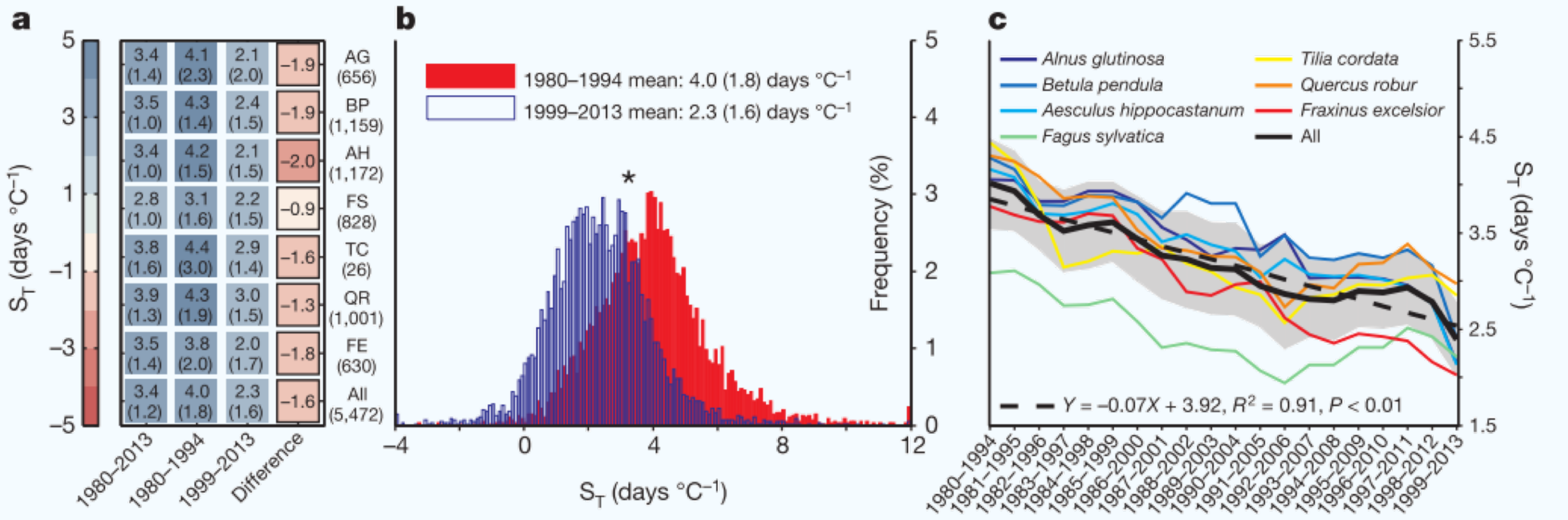
# The response rate of phenology to temperature




**How much SOS is correlated to interannual changes in temperature?**

**Expressed as a partial correlation coefficient between SOS and air temperature ($R_T$).**

**Recent studies have found $R_T$ declined in natural vegetation systems.**




*Fu, et al. Declining global warming effects on the phenology of spring leaf unfolding. 2015. Nature.*

**The extent to which these declining trends will continue in the future remains unclear;**

**Urban phenology study offers a unique opportunity to investigate the changes in $R_T$ in warmer conditions;**

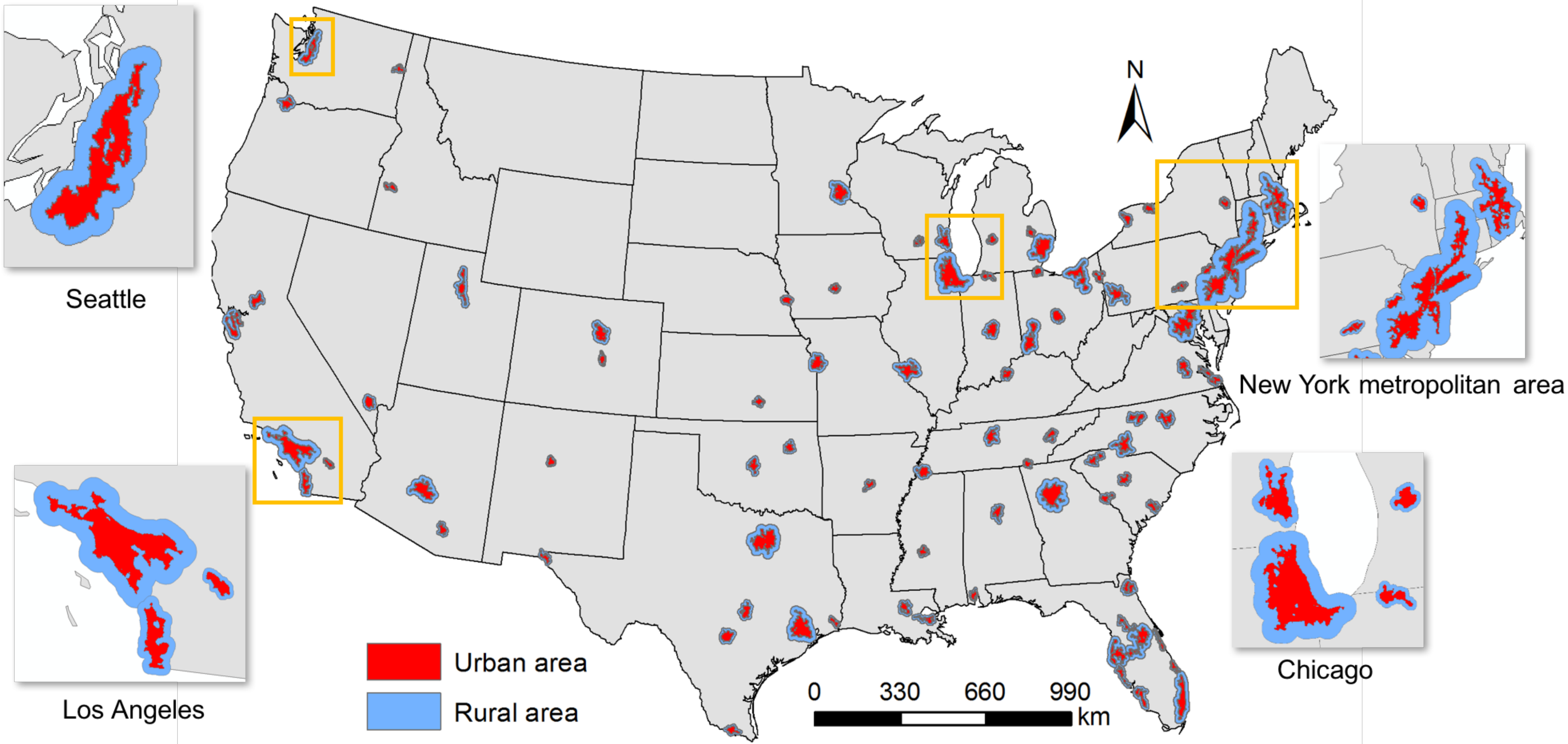
# Research Questions

***Q1: How have SOS and covariation between SOS and temperature ($R_T$) changed in large US cities?***

***Q2: Were these phenological changes and their magnitudes influenced by the background climatic conditions and the modified local environments (e.g., UHI intensity)?***

***Q3: What physiological mechanisms drove these phenological changes?***

# Data and Study Area




- **85 cities with urban areas larger than 500 km$^2$;**
- **MODIS phenology product (2001-2014);**
- **Daymet and TopoWx meteorological observations;**
- **National Land Cover Database to derive urban and other land types.**

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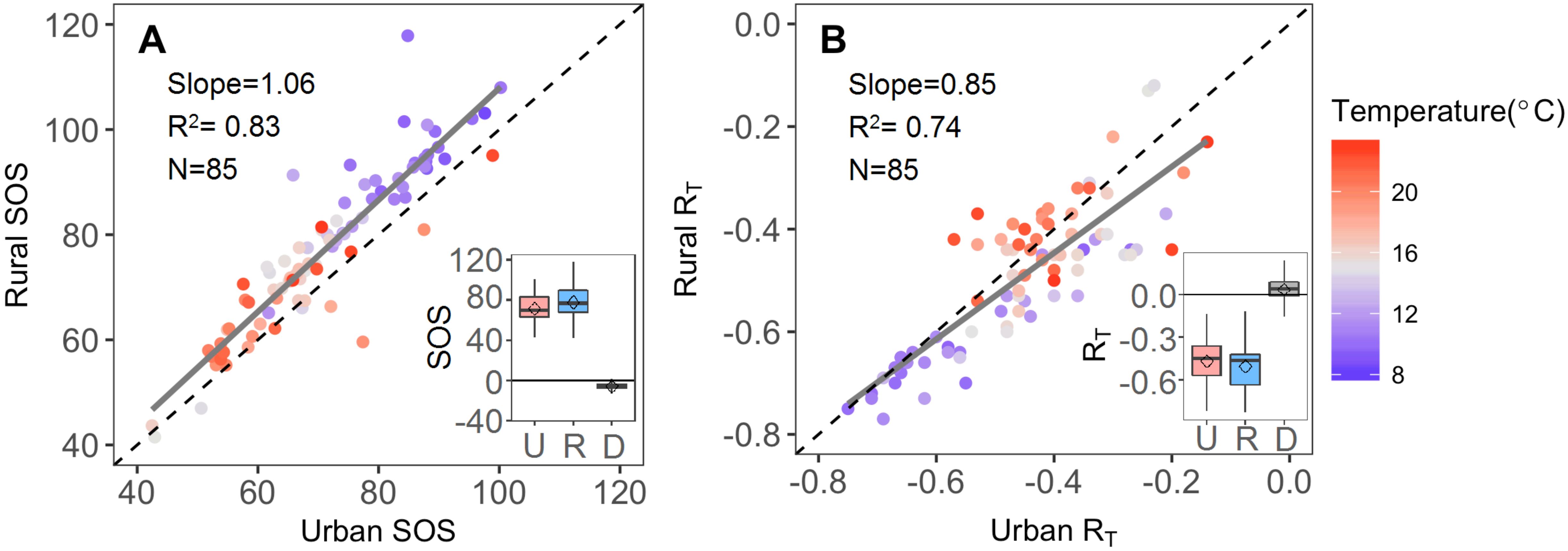
# List of Abbreviations and Acronyms

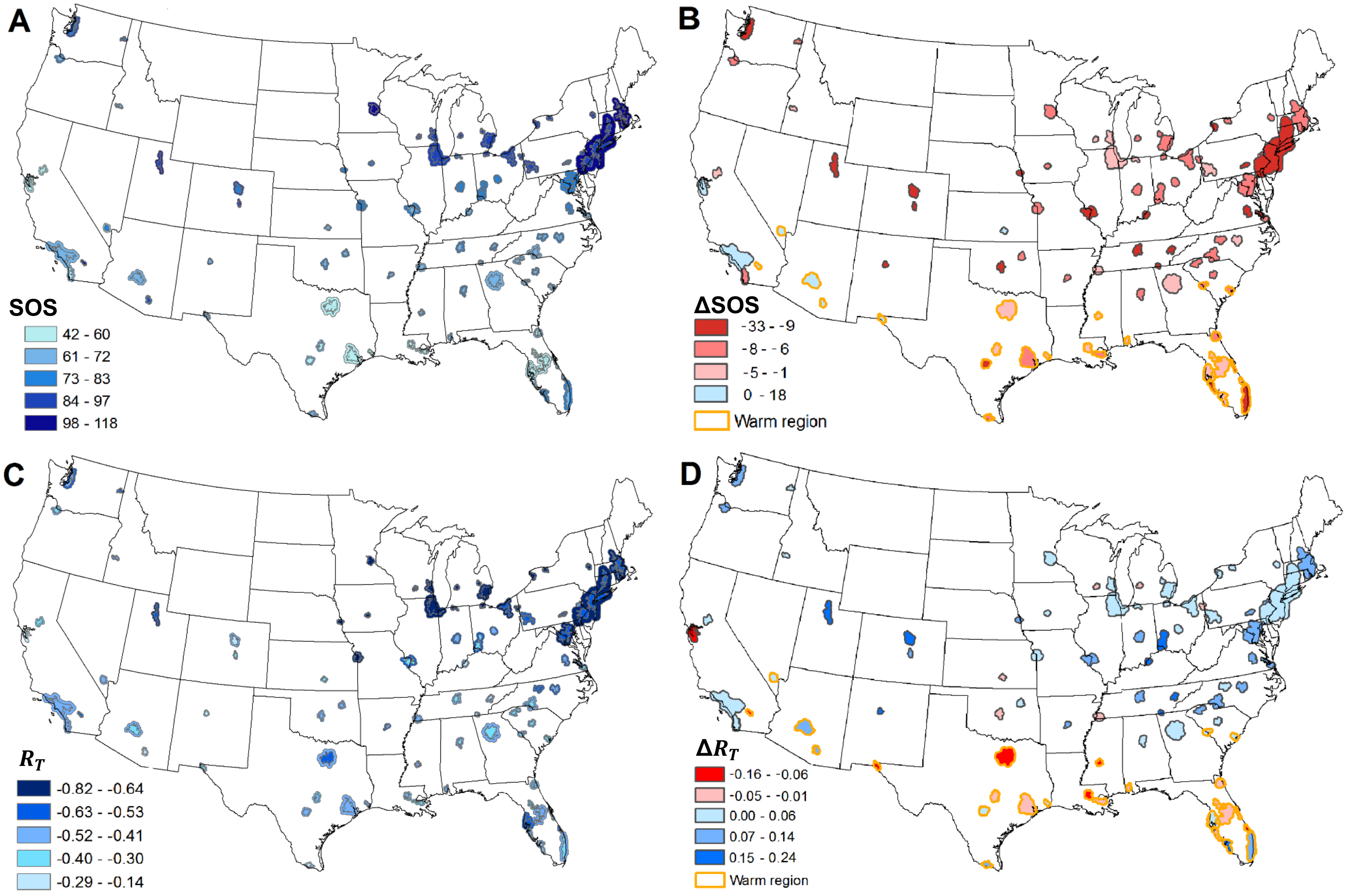
- **SOS**: *start of season*
- **ΔSOS = SOSUrban – SOSRural**
  - *Negative ΔSOS represents an earlier urban SOS*
- $\boldsymbol{R_T}$ : *partial correlation coefficient between SOS and preseason mean air temperature, after statistically controlling for precipitation and shortwave radiation*
- **Δ$\boldsymbol{R_T}$ = $\boldsymbol{R_{T\mathrm{Urban}}}$ – $\boldsymbol{R_{T\mathrm{Rural}}}$**
  - *positive Δ$R_T$ represents a decreased magnitude in SOS response to temperature in urban areas*
- **T**: *averaged annual mean air temperature*
- **ΔT = $\mathbf{T_{Urban}}$ – $\mathbf{T_{rural}}$**
  - *Positive ΔT represents UHI effect*

# Results




**Urban and rural SOS (A) and $R_T$ (B) in 85 study cities.**
**SOS was 6.1 ± 6.3 days earlier in urban areas and 51% (43 cities) demonstrated significantly weaker urban $R_T$.**

# Results




**Spatial pattern of SOS (A), its urban-rural differences (ΔSOS, B), $R_T$(C), and $\Delta R_T$ (D)**

# Research Questions

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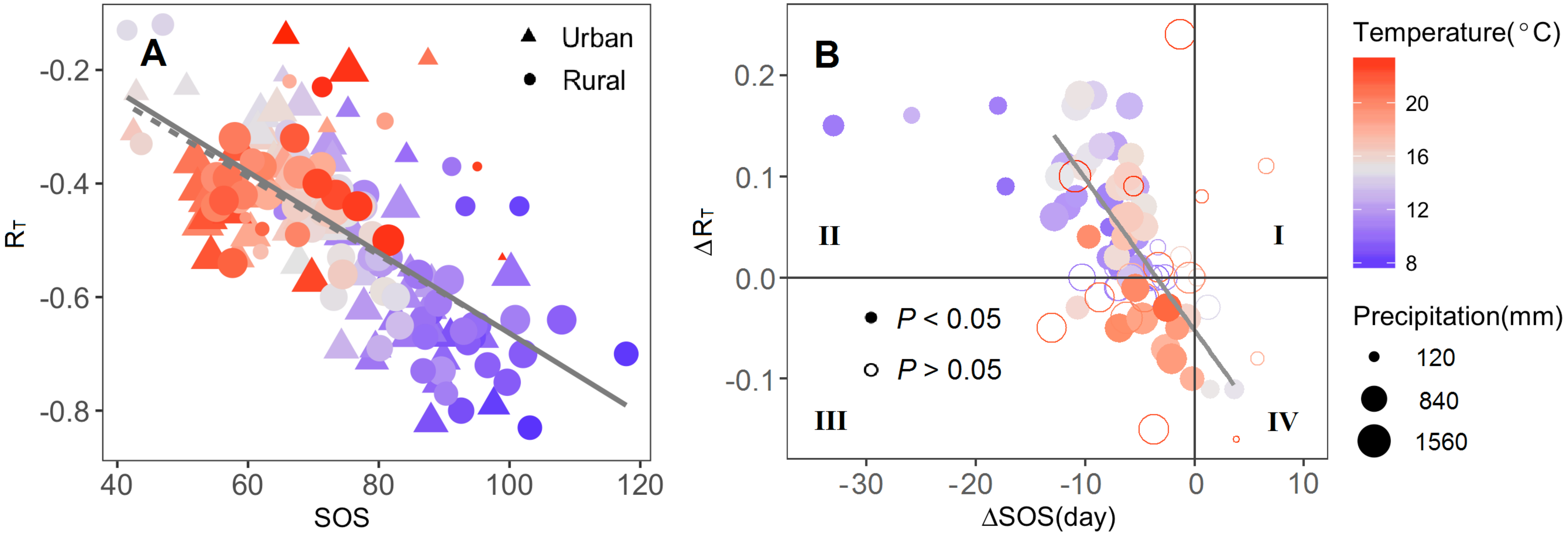
# Results

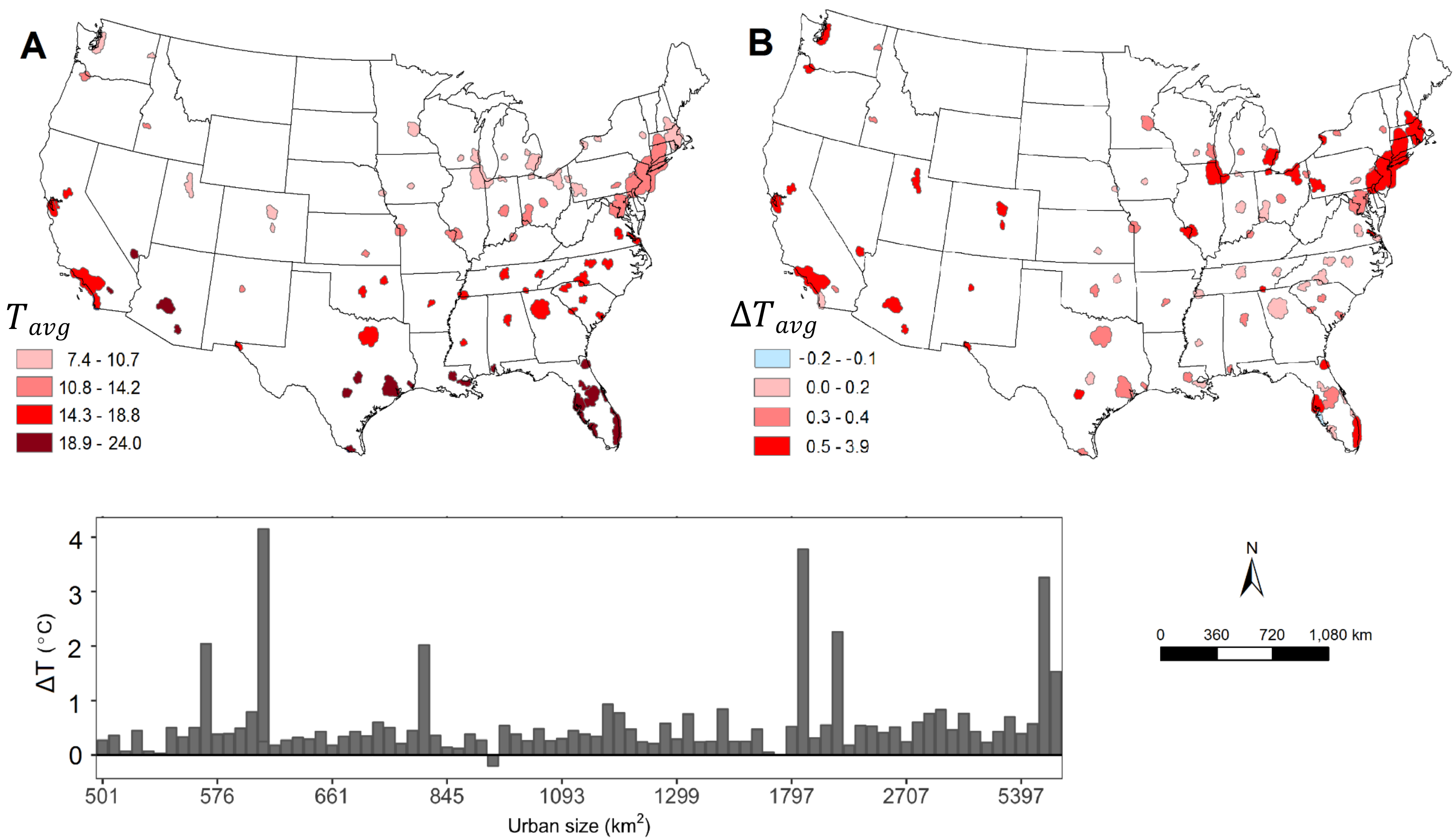
## *Background climatic conditions*




- **The magnitude of $R_T$ significantly decreased (less negative) with the advancement of SOS;**
- **The urban-rural difference in $R_T$ ($\Delta R_T$) negatively correlated with ΔSOS;**
- **Positive $\Delta R_T$ (i.e., reduced urban $R_T$) was found mainly in cities associated with relatively low $T_{avg}$, and on the contrary, negative $\Delta R_T$ (i.e., enhanced urban $R_T$) was predominantly found in cities with high $T_{avg}$**

# Results

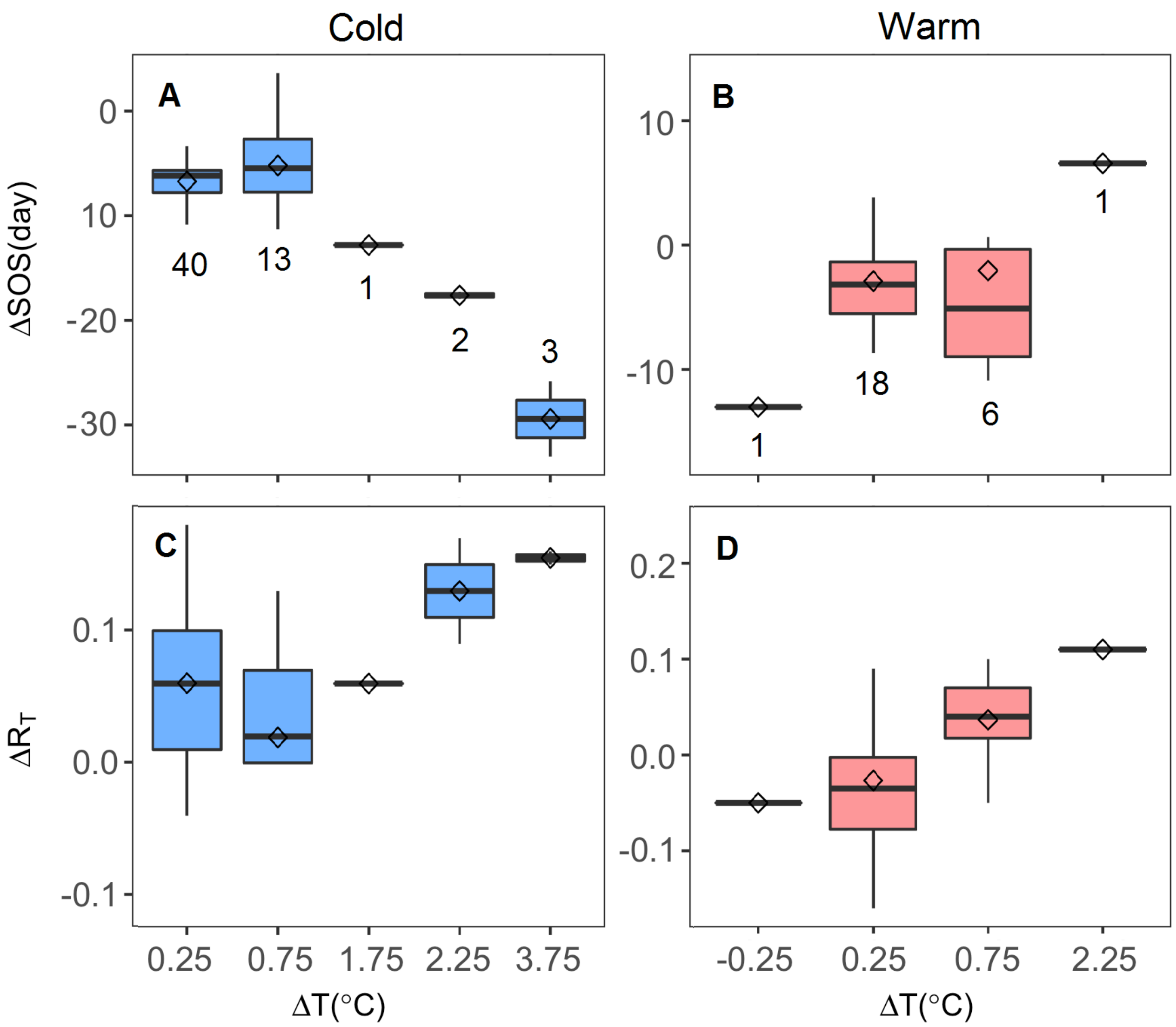
## *Modified local environments*

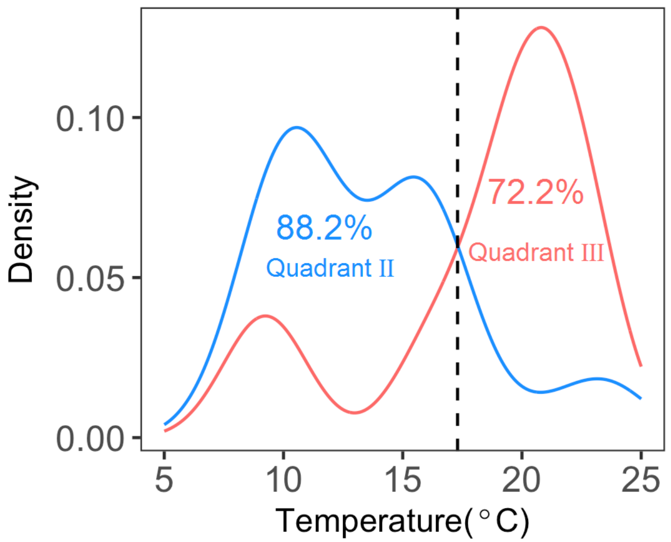



**All the cities except two (98%) showed significant urban heat island effects.**

# Results

## *Modified local environments*




**The $T_{avg}$ threshold distinguishing the cities with positive $\Delta R_T$ from negative $\Delta R_T$ was 17.3 ºC.**

***Cold region:*** **ΔSOS and $\Delta R_T$ significantly decreased at -7.0 days/ºC and increased at 0.04/ºC with the increase in UHI.**

***Warm region:*** **the intensification of UHI strengthened the urban $R_T$ reduction at 0.07/ºC but not SOS.**

# Research Questions

***Q1: How have SOS and covariation between SOS and temperature ($R_T$) changed in large US cities?***

***Q2: Were these phenological changes and their magnitudes influenced by the background climatic conditions and the modified local environments (e.g., UHI intensity)?***

***Q3: What physiological mechanisms drove these phenological changes?***

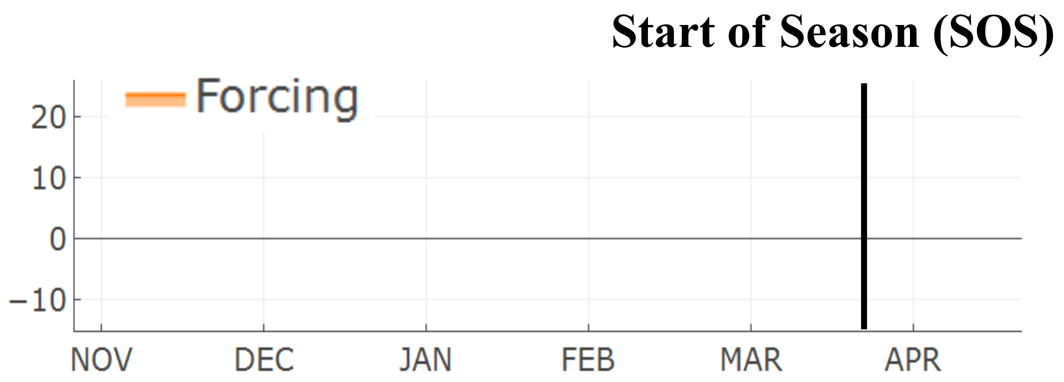
# Phenological models (spring green-up)

### *Growing-degree-day model*

Spring onset is triggered by a certain amount of accumulated daily average temperatures prior to budburst.

Rate of forcing $R_f(t)$

State of forcing $S_f(t) = \sum_{t_0} R_f(x(t))$




### *Chilling model*

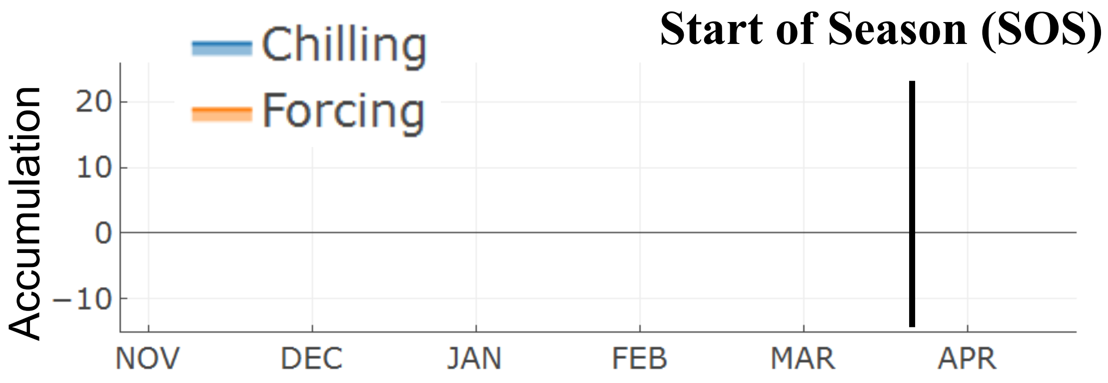
Spring onset is triggered after a certain amount of chilling and forcing prior to budburst.

Rate of forcing $R_f(t)$

State of forcing $S_f(t) = \sum_{t_0} R_f(x(t))$

Rate of chilling $R_c(t)$

State of chilling $S_c(t) = \sum_{t_0} R_c(x(t))$



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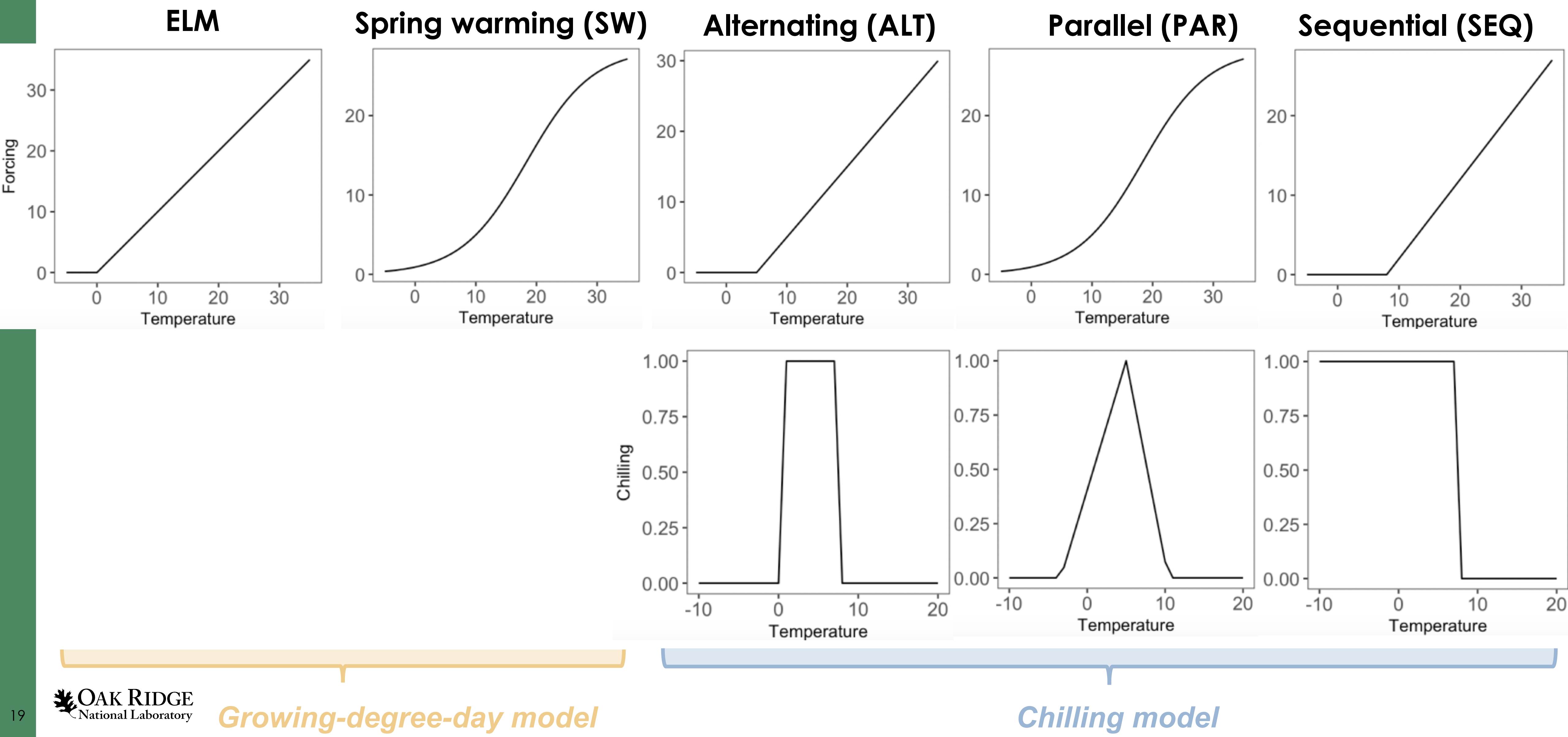
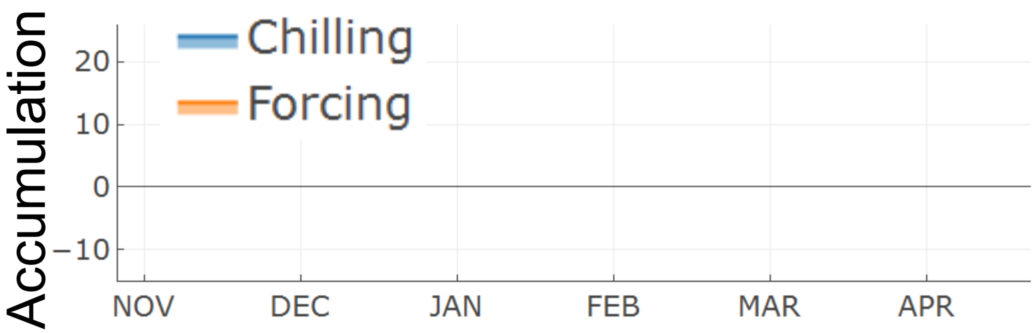
# Phenological models (spring green-up)



# Phenological models (spring green-up)




**Alternating and parallel phenological models assume:**

- Plants accumulate chilling and forcing;
- Spring budburst occurs when forcing meets requirements.
- Required forcing decreases exponentially with chilling increase;

***ALT***

$$R_f(t) = \begin{cases} x(t) - T_{\text{base}} & x(t) > T_{\text{base}} \\ 0 & x(t) \le T_{\text{base}} \end{cases}$$

*State of forcing* $S_f(t) = \sum_{t_0} R_f(x(t))$

$$R_c(t) = \begin{cases} 1 & x(t) < T_{\text{base}} \\ 0 & x(t) \ge T_{\text{base}} \end{cases}$$

*State of chilling* $S_c(t) = \sum_{t_0} R_c(x(t))$

Phenology metric is predicted to occur when $S_f(t) \ge a + b * \exp(c * S_c(t))$, where $c < 0$.

***PAR***

$$R_f(t) = \begin{cases} \dfrac{28.4}{1 + \exp\left(3.4 - 0.185 * x(t)\right)} & x(t) > T_{\text{base}} \\ 0 & x(t) \le T_{\text{base}} \end{cases}$$

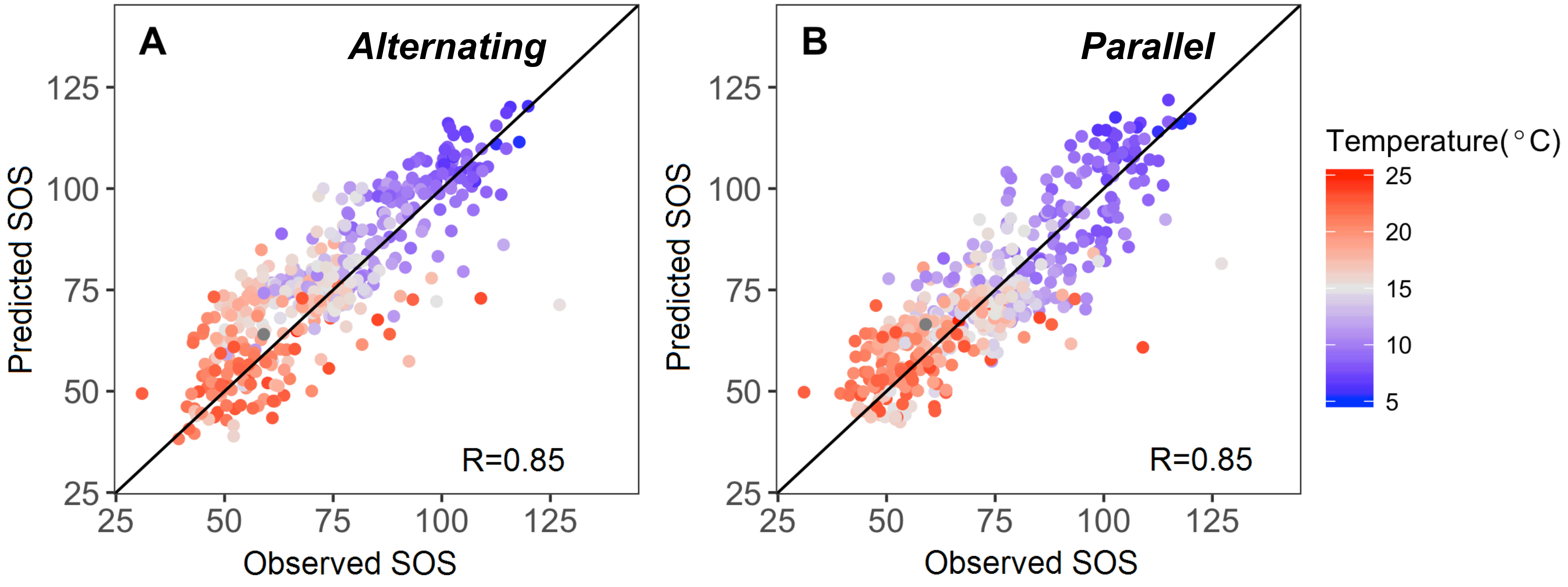
*State of forcing* $S_f(t) = \sum_{t_0} R_f(x(t))$

$$R_c(t) = \begin{cases} 0 & x(t) \ge 10.4 \text{ or } x(t) \le -3.4 \\ \dfrac{x(t) + 3.4}{T_{\text{opt}} + 3.4} & -3.4 < x(t) \le T_{\text{opt}} \\ \dfrac{x(t) - 10.4}{T_{\text{opt}} - 10.4} & T_{\text{opt}} < x(t) < 10.4 \end{cases}$$

*State of chilling* $S_c(t) = \sum_{t_0} R_c(x(t))$

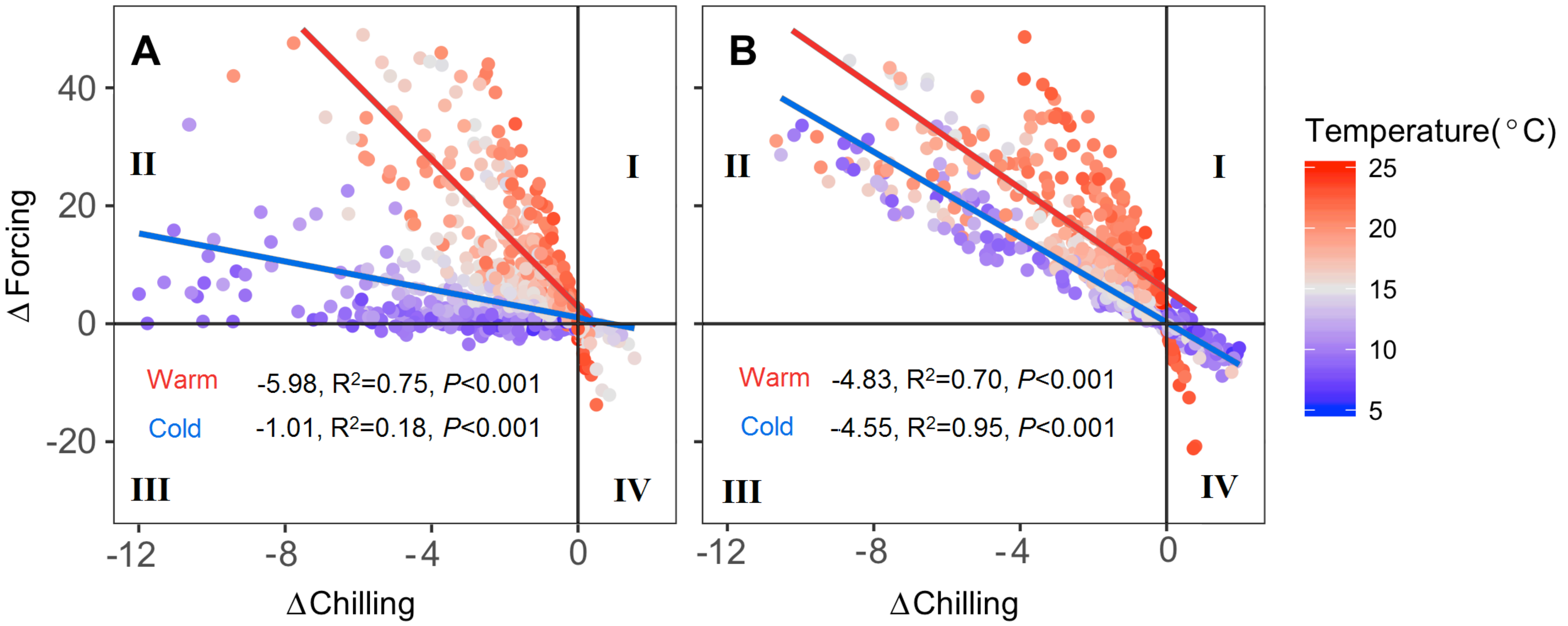
Phenology metric is predicted to occur when $S_f(t) \ge a + b * \exp(S_c(t))$, where $b < 0$.

# Models calibration and evaluation




- **Calibration: 2001-2011, evaluation: 2012-2014;**
- **Both models captured the interannual variation and spatial variability of SOS with a correlation of 0.85 between observation and prediction.**

# Sufficient forcing and chilling deficiency in cities




- **Compared with those in rural areas, urban plants were simulated to accumulate more forcing and less chilling;**
- **More and faster heat accumulation contributed to the earlier SOS, while a decrease in required chilling led to a decline in $R_T$ magnitude in urban areas.**

# Discussion

***To address the changes of SOS and $R_T$ magnitudes, we consider four hypotheses:***

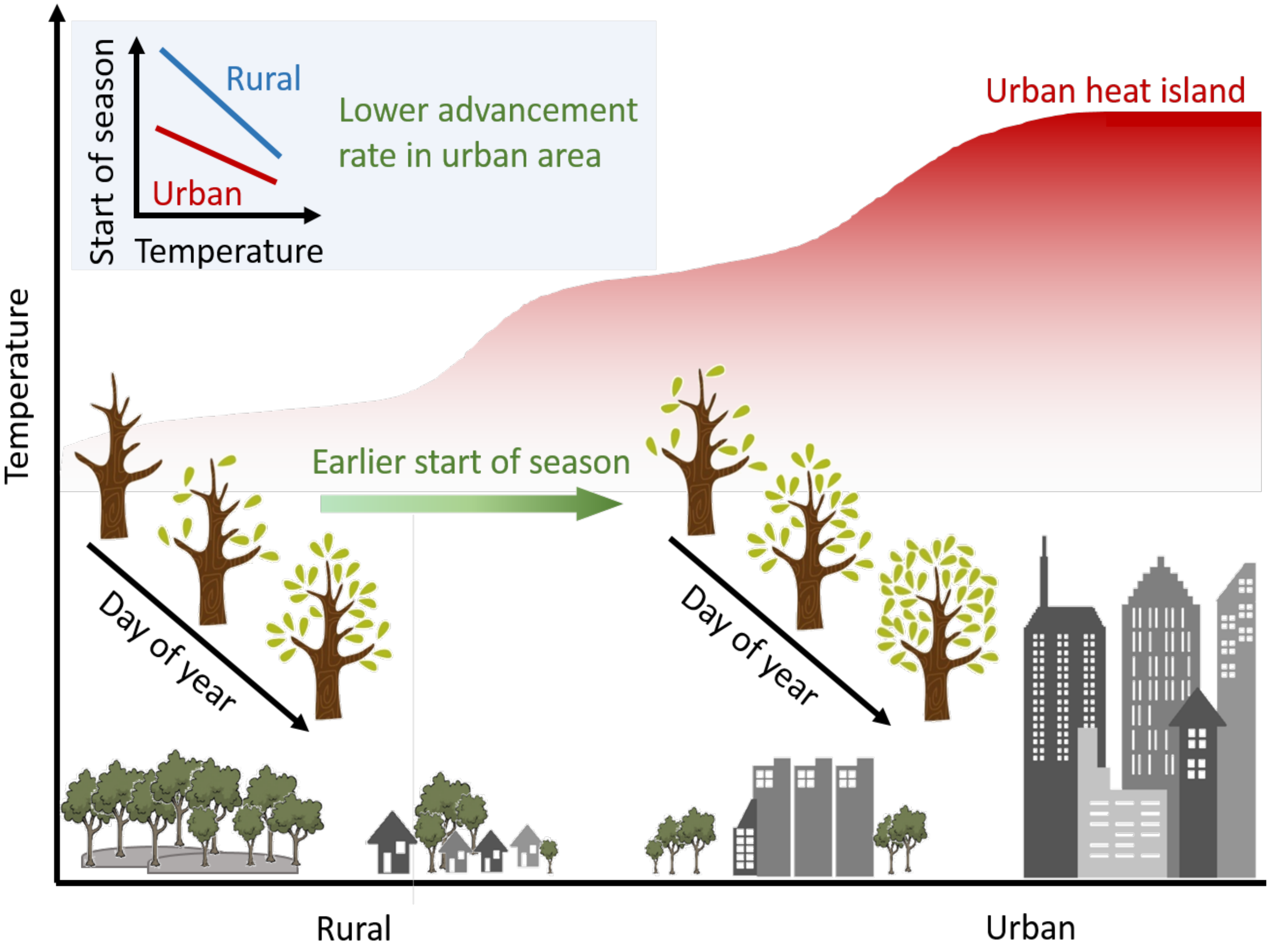
- ***Insufficient chilling:*** if the necessary chilling for dormancy break is not fully met (e.g., warm winters), plants become less responsive to spring warming. Models simulations support this hypothesis.
- ***Thermal budget percentage:*** spring phenology is more sensitive to temperature in colder sites because small absolute changes in temperature constitute greater relative changes in thermal balance under colder conditions. It justifies the reduced urban $R_T$.
- ***Pre-season length:*** climate warming reduces the magnitude of $R_T$ simply by reducing the length of the pre-season due to faster progression toward budburst in spring. No significant changes in pre-season length were found from urban to rural in this study.
- ***Photoperiod:*** could partially contribute to the reduced $R_T$. However, the hard limit of photoperiod was not reached in this study since SOS still advances in warmer conditions.

# Discussion

- Warm region showed enhanced $RT$ indicating the dependence on other environmental cues (e.g., precipitation);
- Other abiotic and biotic factors (e.g., urbanization-induced changes in nitrogen deposition, precipitation regimes, and plant species) could affect urban phenology differently from temperature;
- The rich variety of tree species does not change significantly with urbanization intensity; also, with a considerable amount of native species in cities, mixed phenological signals (native or exotic) still reflect the phenology of tree communities in their geographic regions;
- Phenological models captured the observed SOS variations and more importantly, $\Delta$SOS, indicating that although other factors may influence phenology, urban warming dominated phenological changes in this study.

# Conclusions

- An urban-warming-induced advanced SOS and weakened SOS response to temperature in 85 cities across the United States;
- Such reductions in SOS response were found to be mainly associated with cold regions and their changes correlated well with the intensity of UHI, whereas disparate patterns in SOS response existed in warm regions;
- Increased forcing and reduced chilling were largely responsible for these phenological changes;
- These results suggest that the previously identified advancement in spring phenology in natural ecosystems may continue but that the rate of advancement will likely slow down under future warming, especially in cold areas.




Temperature response of phenology in urban heat islands

# Thanks for questions and comments!

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