Leaf and Bloom Dates

Identification

1. Indicator Description

This indicator examines the timing of first leaf dates and flower bloom dates in lilacs and honeysuckle plants in the contiguous 48 states between 1900 and 2015. The first leaf date in these plants relates to the timing of events that occur in early spring, while the first bloom date is consistent with the timing of later spring events, such as the start of growth in forest vegetation. Lilacs and honeysuckles are especially useful as indicators of spring events because they are widely distributed across most of the contiguous 48 states and widely studied in the peer-reviewed literature. Scientists have very high confidence that recent warming trends in global climate have contributed to the earlier arrival of spring events (IPCC, 2014).

Components of this indicator include:

- Trends in first leaf dates and first bloom dates since 1900, aggregated across the contiguous 48 states (Figure 1).
- A map showing changes in first leaf dates between 1951–1960 and 2006–2015 (Figure 2).
- A map showing changes in first bloom dates between 1951–1960 and 2006–2015 (Figure 3).

2. Revision History

April 2010:	Indicator published.
May 2014:	Combined original Figures 1 and 2 (leaf and bloom date time series) into Figure 1 and updated with data through 2013. Added Figures 2 and 3.
June 2015:	Updated indicator on EPA's website with data through 2014.
August 2016:	Updated indicator with data through 2015.

Data Sources

3. Data Sources

This indicator is based on leaf and bloom observations that are archived by the USA National Phenology Network (USA-NPN) and climate data that are maintained by the National Oceanic and Atmospheric Administration's (NOAA's) National Centers for Environmental Information (NCEI) (formerly the National Climatic Data Center). Data for this indicator were analyzed using a method described by Schwartz et al. (2013).

4. Data Availability

Phenological Observations

This indicator is based in part on observations of lilac and honeysuckle leaf and bloom dates, to the extent that these observations contributed to the development of models. USA-NPN provides online access to historical phenological observations at: www.usanpn.org/data.

Temperature Data

This indicator is based in part on historical daily temperature records, which are publicly available online through NCEI. Individual station measurements and metadata are available through NCEI's website (www.ncdc.noaa.gov/data-access/land-based-station-data).

Model Results

The processed leaf and bloom date data set is not publicly available. EPA obtained the model outputs by contacting Dr. Mark Schwartz at the University of Wisconsin–Milwaukee, who developed the analysis and created the original time series and maps. Results from previous iterations of this analysis have been published in Schwartz et al. (2013) and other papers.

Methodology

5. Data Collection

This indicator was developed using models that relate phenological observations (leaf and bloom dates) to weather and climate variables. These models were developed by analyzing the relationships between two types of measurements: 1) observations of the first leaf emergence and the first flower bloom of the season in lilacs and honeysuckles and 2) temperature data. The models were developed using measurements collected throughout the portions of the Northern Hemisphere where lilacs and/or honeysuckles grow, then applied to temperature records from a larger set of stations throughout the contiguous 48 states.

Phenological Observations

First leaf date is defined as the date on which leaves first start to grow beyond their winter bud tips. First bloom date is defined as the date on which flowers start to open. Ground observations of leaf and bloom dates were gathered by government agencies, field stations, educational institutions, and trained citizen scientists; these observations were then compiled by organizations such as the USA-NPN. These types of phenological observations have a long history and have been used to support a wide range of peer-reviewed studies. See Schwartz et al. (2013) and references cited therein for more information about phenological data collection methods.

Temperature Data

Weather data used to construct, validate, and then apply the models—specifically daily maximum and minimum temperatures—were collected from officially recognized weather stations using standard meteorological instruments. These data have been compiled in NCEI databases such as the TD3200 Daily Summary of the Day data from cooperative weather stations. As described in the methods for an earlier version of this analysis (Schwartz et al., 2006), station data were used rather than gridded values, "primarily because of the undesirable homogenizing effect that widely available coarse-resolution grid point data can have on spatial differences, resulting in artificial uniformity of processed outputs..." (Schwartz and Reiter, 2000; Schwartz and Chen, 2002; Menzel et al., 2003). Ultimately, 2,860 weather stations were selected according to the following criteria:

- Provide for the best temporal and spatial coverage possible. At some stations, the period of record includes most of the 20th century.
- Have at least 25 of 30 years during the 1981–2010 baseline period, with no 30-day periods missing more than 10 days of data.
- Have sufficient spring–summer warmth to generate valid model output.

For more information on the procedures used to obtain temperature data, see Schwartz et al. (2013) and references cited therein.

6. Indicator Derivation

Daily temperature data and observations of first leaf and bloom dates were used to construct and validate a set of models that relate phenological observations to weather and climate variables (specifically daily maximum and minimum temperatures). These models were developed for the entire Northern Hemisphere and validated at 378 sites in Germany, Estonia, China, and the United States.

Once the models were validated, they were applied to locations throughout the contiguous 48 states using temperature records from 1900 to 2015. Even if actual phenological observations were not collected at a particular station, the models essentially predict phenological behavior based on observed daily maximum and minimum temperatures, allowing the user to estimate the date of first leaf and first bloom for each year at that location. The value of these models is that they can estimate the onset of spring events in locations and time periods where actual lilac and honeysuckle observations are sparse. In the case of this indicator, the models have been applied to a time period that is much longer than most phenological observation records. The models have also been extended to areas of the contiguous 48 states where lilacs and honeysuckles do not actually grow—mainly parts of the South and the West coast where winter is too warm to provide the extended chilling that these plants need in order to bloom the following spring. This step was taken to provide more complete spatial coverage.

This indicator was developed by applying phenological models to nearly 3,000 sites in the contiguous 48 states where sufficient weather data have been collected. The exact number of sites varies from year to year over the period 1900–2015 depending on data availability. This is a much larger set of sites than the earlier (2014) version of the indicator, which was based on a set of 779 sites.

After running the models, analysts looked at each location and compared the first leaf date and first bloom date in each year with the average leaf date and bloom date for 1981 to 2010, which was established as a "climate normal" or baseline. This step resulted in a data set that lists each station along with the "departure from normal" for each year—measured in days—for each component of the indicator (leaf date and bloom date). Note that 1981 to 2010 represents an arbitrary baseline for comparison, and choosing a different baseline period would shift the observed long-term trends up or down but would not alter the shape, magnitude, or statistical significance of the trends.

Figure 1. First Leaf and Bloom Dates in the Contiguous 48 States, 1900–2015

EPA obtained a data set listing annual departure from normal for each station, then performed some additional steps to create Figure 1. For each component of the indicator (leaf date and bloom date), EPA aggregated the data for each year to determine an average departure from normal across all stations. This step involved calculating an unweighted arithmetic mean of all stations with data in a given year. The aggregated annual trend line appears as a thin curve in each figure. To smooth out some of the year-to-year variability, EPA also calculated a nine-year weighted moving average for each component of the indicator. This curve appears as a thick line in each figure, with each value plotted at the center of the corresponding nine-year window. For example, the average from 2000 to 2008 is plotted at year 2004. This nine-year average was constructed using a normal curve weighting procedure that preferentially weights values closer to the center of the window. Weighting coefficients for values 1 through 9, respectively, were as follows: 0.0076, 0.036, 0.1094, 0.214, 0.266, 0.214, 0.1094, 0.036, 0.0076. This procedure was recommended by the authors of Schwartz et al. (2013) as an appropriate way to reduce some of the “noise” inherent in annual phenology data.

EPA used endpoint padding to extend the nine-year smoothed lines all the way to the ends of the period of record. Per the data provider’s recommendation, EPA calculated smoothed values centered at 2012, 2013, 2014, and 2015 by inserting the 2011–2015 average into the equation in place of the as-yet unreported annual data points for 2016 and beyond. EPA used an equivalent approach at the beginning of the time series.

Figures 2 and 3. Change in First Leaf and Bloom Dates Between 1951–1960 and 2006–2015

To show spatial patterns in leaf and bloom changes, Figures 2 and 3 compare the most recent decade of data with the decade from 1951 to 1960 at individual stations. The 1950s were chosen as a baseline period to be consistent with the analysis published by Schwartz et al. (2013), who noted that broad changes in the timing of spring events appeared to start around the 1950s. To create the maps, EPA calculated the average departure from normal during each 10-year period and then calculated the difference between the two periods. The maps are restricted to stations that had at least eight years of valid data in both 10-year periods; 1,472 stations met these criteria.

For more information on the procedures used to develop, test, and apply the models for this indicator, see Schwartz et al. (2013) and references cited therein.

Indicator Development

The 2010 edition of EPA’s *Climate Change Indicators in the United States* report presented an earlier version of this indicator based on an analysis published in Schwartz et al. (2006). That analysis was referred to as the Spring Indices (SI). The team that developed the original SI subsequently developed an enhanced version of their algorithm, which is referred to as the Extended Spring Indices (SI-x). EPA adopted the SI-x approach for the 2012 edition of *Climate Change Indicators in the United States*. The SI-x represents an extension of the original SI because it can now characterize the timing of spring events in areas where lilacs and honeysuckles do not grow. Additional details about the SI-x are discussed in Schwartz et al. (2013).

For the 2014 edition of this indicator, EPA added a set of maps (Figures 2 and 3) to provide a more robust depiction of regional variations. These maps were published in Schwartz et al. (2013) and have since been updated with more recent data.

The 2015 update of this indicator included an expansion in the number of weather stations used to nearly 3,000 sites, compared with the previous 2014 version, which was based on 779 sites. This change was possible due to the availability of improved historical temperature data.

7. Quality Assurance and Quality Control

Phenological Observations

Quality assurance and quality control (QA/QC) procedures for phenological observations are not readily available.

Temperature Data

Most of the daily maximum and minimum temperature values were evaluated and cleaned to remove questionable values as part of their source development. For example, several papers have been written about the methods of processing and correcting historical climate data for NCEI's U.S. Historical Climatology Network (USHCN) and Global Historical Climatology Network (GHCN). NCEI's websites at: www.ncdc.noaa.gov/oa/climate/research/ushcn and www.ncdc.noaa.gov/ghcnm/v3.php describe the underlying methods and cite peer-reviewed publications for justification.

Before applying the model, all temperature data were checked to ensure that no daily minimum temperature value was larger than the corresponding daily maximum temperature value (Schwartz et al., 2006).

Model Results

QA/QC procedures are not readily available regarding the use of the models and processing the results. These models and results have been published in numerous peer-reviewed studies, however, suggesting a high level of QA/QC and review. For more information about the development and application of these models, see Schwartz et al. (2013), McCabe et al. (2012), and the references cited therein.

Analysis

8. Comparability Over Time and Space

Phenological Observations

For consistency, the phenological observations used to develop this indicator were restricted to certain cloned species of lilac and honeysuckle. Using cloned species minimizes the influence of genetic differences in plant response to temperature cues, and it helps to ensure consistency over time and space.

Temperature Data

NCEI's databases have undergone extensive testing to identify errors and biases in the data and either remove these stations from the time series or apply scientifically appropriate correction factors to improve the utility of the data. In particular, these corrections address changes in the time-of-day of observation, advances in instrumentation, and station location changes. Homogeneity testing and data correction methods are described in more than a dozen peer-reviewed scientific papers by NCEI. Data corrections were developed to specifically address potential problems in trend estimation of the rates of warming or cooling.

Model Results

The same model was applied consistently over time and space. Figure 1 generalizes results over space by averaging station-level departures from normal in order to determine the aggregate departure from normal for each year. This step uses a simple unweighted arithmetic average, which is appropriate given the national scale of this indicator and the large number of weather stations spread across the contiguous 48 states.

9. Data Limitations

Factors that may impact the confidence, application, or conclusions drawn from this indicator are as follows:

1. Plant phenological events are studied using several data collection methods, including satellite images, models, and direct observations. The use of varying data collection methods in addition to the use of different phenological indicators (such as leaf or bloom dates for different types of plants) can lead to a range of estimates of the arrival of spring.

2. Climate is not the only factor that can affect phenology. Observed variations can also reflect plant genetics, changes in the surrounding ecosystem, and other factors. This indicator minimizes genetic influences by relying on cloned plant species, however (that is, plants with no genetic differences).

10. Sources of Uncertainty

Error estimates are not readily available for the underlying temperature data upon which this indicator is based. It is generally understood that uncertainties in the temperature data increase as one goes back in time, as there are fewer stations early in the record. These uncertainties are not sufficient, however, to mislead the user about fundamental trends in the data.

In aggregating station-level "departure from normal" data into an average departure for each year, EPA calculated the standard error of each component of Figure 1 (leaf date and bloom date) in each year. Standard errors range from 0.2 days to 0.4 days for leaf date, and from 0.1 days to 0.4 days for bloom date, depending on the year.

Uncertainty has not been calculated for the individual station-level changes shown in Figures 2 and 3.

Schwartz et al. (2013) provide error estimates for the models. The use of modeled data should not detract from the conclusions that can be inferred from the indicator. These models have been extensively tested and refined over time and space such that they offer good certainty.

11. Sources of Variability

Temperatures naturally vary from year to year, which can strongly influence leaf and bloom dates. To smooth out some of the year-to-year variability, EPA calculated a nine-year weighted moving average for each component of this indicator in Figure 1, and EPA created the maps in Figures 2 and 3 based on 10-year averages for each station.

12. Statistical/Trend Analysis

Statistical testing of individual station trends within the contiguous 48 states suggests that many of these trends are not significant. Other studies (e.g., Schwartz et al., 2006) have come to similar conclusions, finding that trends in the earlier onset of spring at individual stations are much stronger in Canada and parts of Eurasia than they are in the contiguous 48 states. In part as a result of these findings, Figure 1 focuses on aggregate trends across the contiguous 48 states, which should be more statistically robust than individual station trends. However, the aggregate trends still are not statistically significant ($p<0.05$) over the entire period of record, based on a standard t-test statistic.

References

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