

eLetter response

The principles of causation and statistical inference in phenological studies

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In his eLetter, Bigler suggests that our analysis (1) led to biased effect sizes and standard errors by including temperatures recorded after the observed leaf senescence dates. He proposes that our study implies “backward causation”, where an effect appears to precede its cause, allowing a later event to impact an earlier one. However, this interpretation is incorrect. Such an assessment misrepresents our analyses and the statistical relationships between temperature periods and phenological dates.

It is evident that any temperature occurring post-senescence cannot causally influence the senescence dates. This is clearly seen in Fig. 2a of our paper (1), which indicates no correlation between September temperatures and the onset dates of senescence, typically in August. Our analysis does not imply backward causation; instead, it confirms the expected

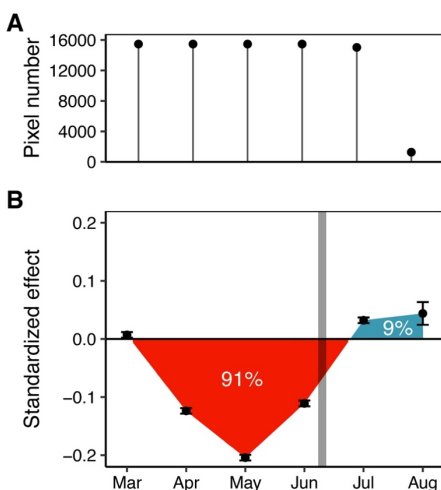


Fig. 1. Relationship between temperature and timing of autumn leaf senescence in northern forests. Autumn phenology is represented as EOS₁₀ dates from satellite observations. **A)** This bar chart depicts the distribution of sample sizes (number of pixels) across different months, used for analyzing autumn leaf senescence timing. The analysis only includes months where the average senescence date for a pixel occurs after the 15th of each month. Consequently, this criterion led to the exclusion of 3% of the pixels for July and 92% for August. **B)** The graph illustrates the relationship between the mean monthly daytime temperature (T_{day}) and EOS₁₀ dates, as derived from multiple linear regression models (see Fig. 2A in the original paper). The means are presented along with \pm 95% confidence ranges. The percentages shown indicate the total positive and negative areas under the curve, representing the relative effects of seasonal T_{day} on advancing versus delaying autumn leaf senescence.

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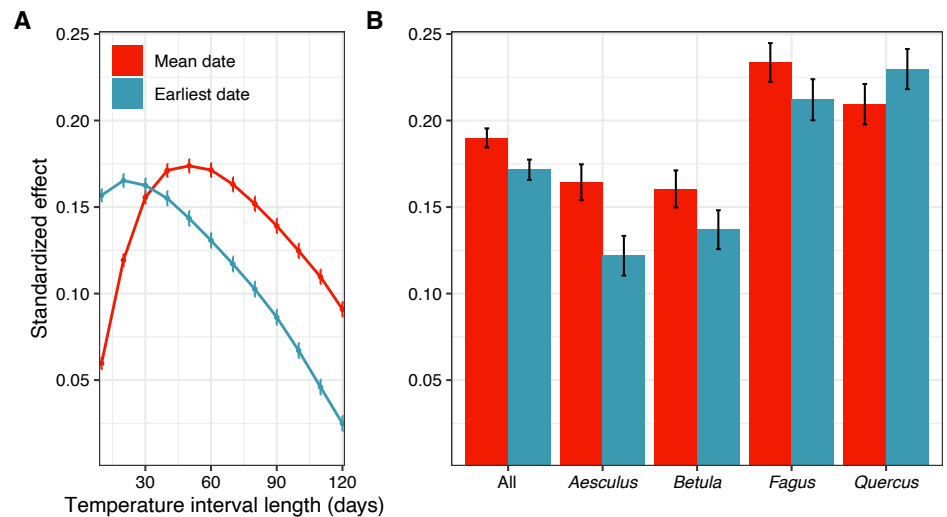


Fig. 2. Effect of autumn temperature on end-of-season (EOS₅₀) dates in the PEP725 dataset. This figure examines the influence of autumn temperatures prior to both the mean (red colors) and the earliest EOS₅₀ dates (blue colors) on the EOS₅₀ dates themselves. **A)** Standardized regression coefficients (means \pm 95% confidence intervals) for the univariate correlations between autumn temperature intervals and EOS₅₀ dates. Linear regressions were performed to establish the relationship between EOS₅₀ dates and night-time temperature intervals ranging from 10 to 120 days (with 10-day steps) before the mean EOS₅₀ date and before the earliest EOS₅₀ date in each time series. Models were run separately for all 12,759 time series in the data set. **B)** Standardized regression coefficients from univariate correlations between optimal autumn temperature intervals and EOS₅₀ dates. For each time series, “optimal autumn intervals” are defined as periods during which temperature variations explain most of the changes in EOS₅₀ dates, indicated by the highest coefficient of determination values. The figure presents the mean effects (\pm 95% confidence intervals), both for the overall dataset and separately for the four European species included in the PEP725 dataset. The EOS₅₀ is defined as the date by which 50% of leaves have lost their green color.

outcome: temperatures following the senescence date have no impact on it.

To further affirm the robustness of our estimated effect sizes for July and August, we conducted an additional analysis. This analysis only included months where the mean senescence date for a pixel fell after the 15th of each month. Consequently, this approach led to the exclusion of 3% and 92% of the 15,459 pixels for July and August, respectively. As shown in Fig. 1, the outcomes are consistent, affirming that the effects reported in our study (1) are unbiased.

Bigler’s suggestion that other aspects of our analysis might have led to biased effects is also unfounded. In phenological studies, it is common practice to correlate climate data from before a mean phenological date with the observed dates, in order to estimate the phenological sensitivity to climate variables (2, 3). Typically, the duration of the preceding period is adjusted to capture the maximum effect, as illustrated in Fig. S18 of our paper (1). In these analyses, while some senescence dates inevitably fall before the mean date, this does not necessarily imply an underestimation of the actual effect. To test Bigler’s assumption, we conducted an additional

analysis using temperature data up to the earliest observed senescence date for each time series. This means all temperature periods for the correlation analysis precede every observed senescence date. As shown in Fig. 2, this method yielded slightly lower effect sizes, contradicting Bigler’s notion of an underestimation. The reason for this outcome is that by limiting temperature data to earlier dates, temperatures occurring during the actual senescence period are disregarded. Yet, as extensively demonstrated in our paper (1), temperature greatly influences the progression of senescence.

In conclusion, our finding that the effect of climate warming on the timing of autumn leaf senescence undergoes a reversal after the summer solstice is unbiased and unaffected by backward causation.

REFERENCES AND NOTES

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