## 2.a.1 Phenology of primary producers

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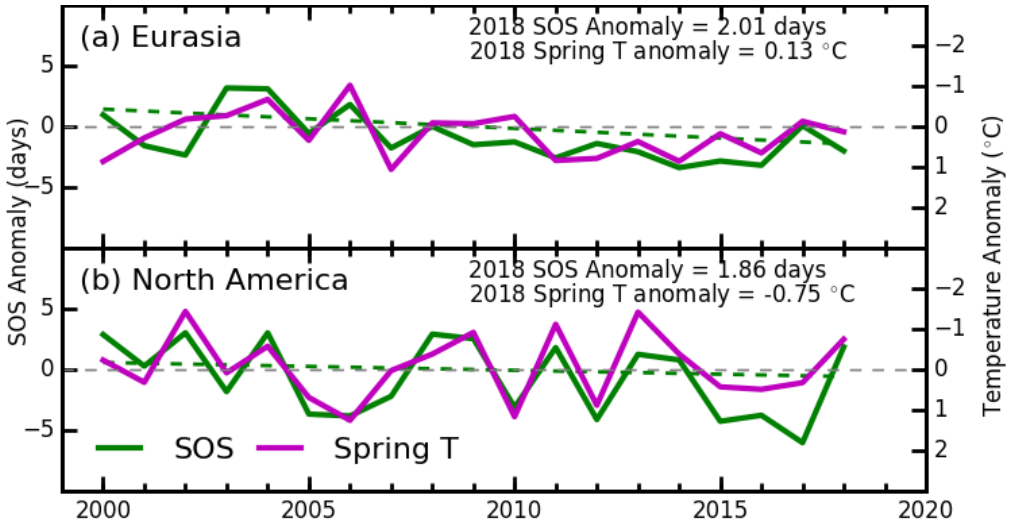
Following the sidebar on phenology in the 2017 State of the Climate Report (Hemming et al. 2018), this is a new section dedicated to phenology, the study of relationships between climate and recurring events in nature (Demarée and Rutishauser 2011). We compare Northern Hemisphere spring growth of primary producers (terrestrial vegetation and lake plankton), utilising records from satellite remote sensing and site-level monitoring. Satellite remote sensing provides large-scale and reasonably long-term records of land surface phenology by tracking the seasonal trajectory of vegetation greenness, and these are complemented by individual site records, which provide a unique, ground-level perspective on phenology at the organism-to-ecosystem level.

The Moderate Resolution Imaging Spectroradiometers (MODIS) on the NASA Terra and Aqua platforms have recorded daily radiometric properties of the entire globe with high spatial, spectral, and radiometric resolution since 2000 and 2002, respectively. During 2018, the MODIS-derived normalized difference vegetation index (NDVI) (Park et al. 2016), revealed a clear spatial contrast in the timing of vegetation growing season onset (SOS) across the Northern Hemisphere (>30°N), compared to the 2000-2010 baseline period (Plate X). The continental mean day of year of SOS during the baseline was 140 (20$^{th}$ May) for North America (NA) and 135 (15$^{th}$ May) for Eurasia (EA), whereas, in 2018, mean SOS in NA was 1.9 days later and in EA was 2.0 days earlier. The hemispheric pattern is correlated with mean spring (March-May) temperature anomaly across each region (NA: r = 0.81, EA: r

= 0.60), which was 0.8 °C cooler in NA and 0.1 °C warmer in EA, compared to the baseline. In the context of long-term trends, EA shows a significant advancement in SOS over the last 19 years (EA: −1.5 ± 0.59 days per decade, $p$ = 0.019; NA: −0.64 ± 0.41 days per decade, $p$ = 0.134).




(c) Start of Season (SOS)

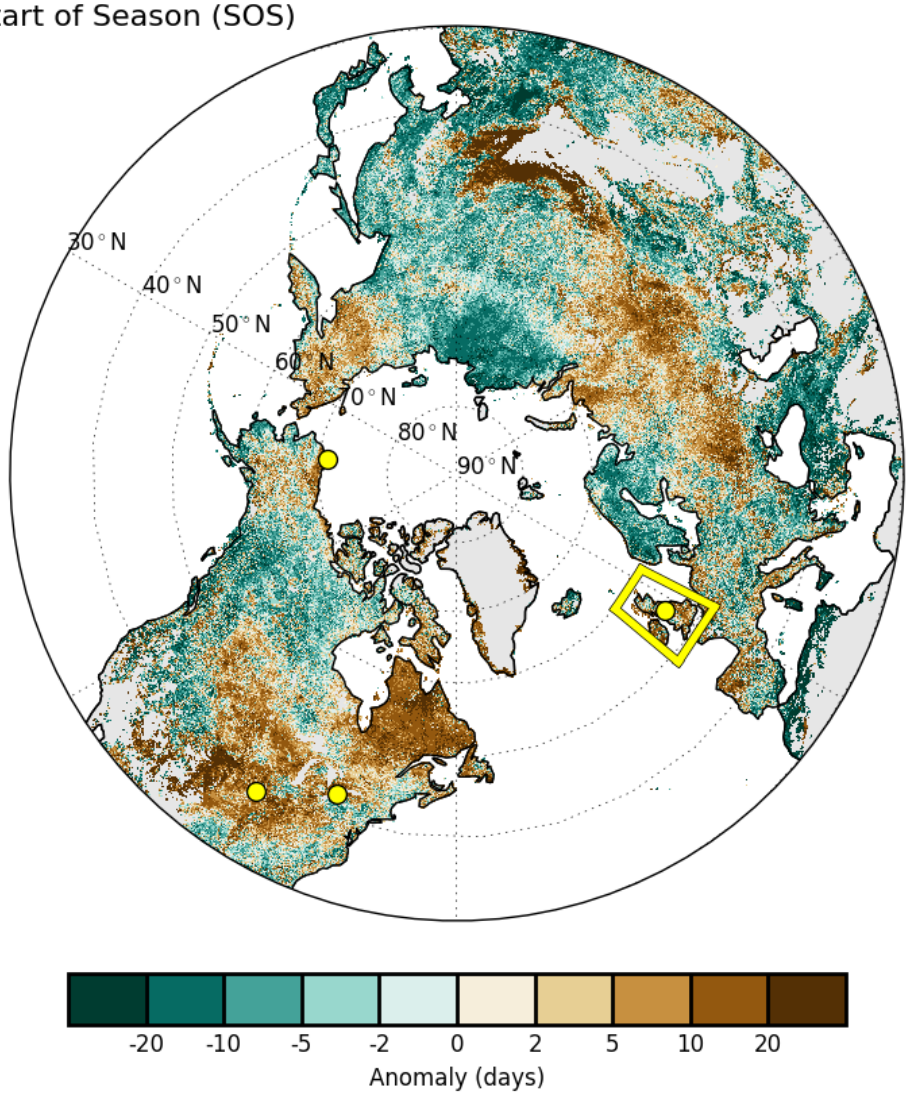


**Plate X. Time series (and linear trend line) of area-mean anomalies (relative to 2000-2010 baseline) in MODIS NDVI-based vegetation growing season onset (SOS, green) and spring (March-May) temperature (magenta) for (a) Eurasia, and (b) North America. Note temperature scale reversal. Spatial pattern of SOS anomaly in 2018 with respect to the baseline (c). Highlighted points and box identify the location of sites shown in Plate Xx and discussed in the text (in USA from west to east: Barrow (Alaska), Ozarks (Missouri), Turkey Point (Maryland), and in UK, Windermere lake and UK mean).**

To compare with the large-scale satellite-derived SOS, we show spring phenology indicators from a range of surface sites in the North American PhenoCam network, the UK Nature's Calendar network and the North and South Basins of Windermere, UK.

The PhenoCam network uses digital camera imagery to track vegetation phenology, at fine spatial and temporal resolution, across North America (Richardson 2018). A "vegetation greenness index" (the green chromatic coordinate; Sonnentag et al. 2012), calculated from the images, generally aligns well with the spatial and temporal patterns of phenology derived from satellite remote sensing (Richardson et al. 2018; Zhang et al. 2018). For example, over the 2008-2018 period, camera-derived start-of-spring transition dates for Harvard Forest, a deciduous forest in Massachusetts, USA, correlate well with the MODIS SOS estimates described above ($r$ = 0.82, $n$ = 11 years).

Because relatively few PhenoCams were deployed before 2010, it is not possible to reference the 2018 SOS against a 2000-2010 baseline. However, relative to 2017, MODIS data indicate that the 2018 SOS was delayed for 75 % of the land area in North America above 30 °N. These patterns are supported by PhenoCam imagery, which also provides visual context for the phenological anomalies, as illustrated for three sites spanning a wide geographic range (Plate Xx).

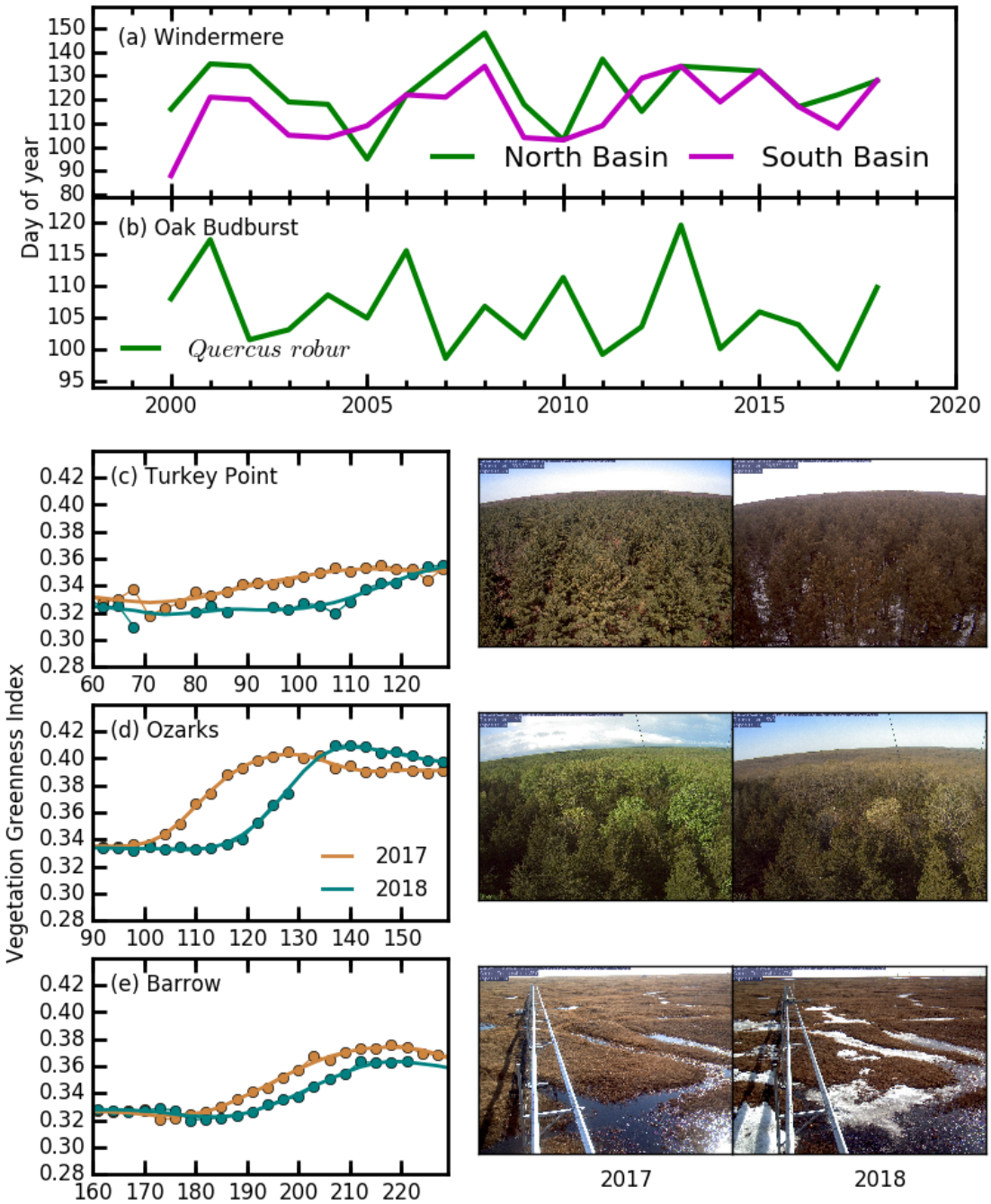



**Plate Xx. Time series of day of year of (a) spring phytoplankton peak in the North and South Basins of lake Windermere, UK, and (b) UK mean budburst of Pedunculate Oak (*Quercus robur*) monitored by Nature's Calendar. (c) Spring trajectory for 2017 (advanced) and 2018 (delayed) vegetation greenness index derived from PhenoCam imagery at three sites across North America - Barrow (upper), Ozarks (middle), Turkey Point (lower). PhenoCam photographs show visually obvious differences in the state of each ecosystem on the same day of year (Barrow = 27th June, Ozarks = 30th April, Turkey Point = 18th April) in 2017 (middle column) and 2018 (right column).**

Nature's Calendar is a UK-wide Citizen Science scheme to record phenology coordinated by the Woodland Trust since 2000. Amongst other events, recorders register "budburst", when leaf buds of Pedunculate Oak (*Quercus robur*) first burst and reveal their leaf colour. During 2018, the UK mean budburst (based on 270 observations) for this species was on day 110 (20th April), three days later than mean budburst during the 2000-2010 baseline (Plate Xx). This is consistent with a slightly later MODIS-derived SOS for UK in 2018, and with a 1°C colder January-March Central England Temperature in 2018.

*In-situ* monitoring of England's largest lake, Windermere, has been conducted since the 1940s by the Centre for Ecology & Hydrology, its predecessor organisations, and the Freshwater Biological Association. Fortnightly data on lake water concentrations of the photosynthetic pigment chlorophyll-*a* have been used to derive the timing of the spring phytoplankton peak, in both the North and South basins (Plate Xx). During the 2000-2010 baseline, the mean day of year of spring bloom was 122 (2nd May) in North Basin and 112 (22nd April) in South Basin, compared with day 128 (8th May) in both basins in 2018; a delay in spring bloom of approximately 6 and 16 days, respectively, relative to the baseline. This later start of season in 2018 concurs with the Nature's Calendar observations of UK budburst of *Q. robur* and the mean large-scale MODIS SOS indicator for UK.

The analyses presented here clearly show the biological impacts of climate variations on the highlighted terrestrial and aquatic ecosystems. In future years, we aim to build on the analyses presented here by utilising a wider range of phenological indicators and locations.

**References**

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**Datasets used and their URLs**

- Satellite land surface phenology is derived from both MODIS Vegetation Indices and Snow Cover products that are available from, respectively:
  https://lpdaac.usgs.gov/dataset_discovery/modis/modis_products_table/mod13c1_v006
  https://nsidc.org/data/MOD10C1/versions/6
- PhenoCam imagery and data are publicly available from:
  http://phenocam.sr.unh.edu
- Nature's Calendar data are available from:
  https://naturescalendar.woodlandtrust.org.uk/
- Windermere data are available from:
  https://catalogue.ceh.ac.uk/documents/e3c4d368-215d-49b2-8e12-74c99c4c3a9d)
  https://catalogue.ceh.ac.uk/documents/f385b60a-2a6b-432e-aadd-a9690415a0ca

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**Summary bullet points**

- In 2018, the timing of Northern Hemisphere vegetation growing season onset (SOS), derived from MODIS satellite monitoring, was on average 1.9 days later across North America and 2 days earlier across Eurasia, relative to the 2000-2010 baseline. These differences relate to cooler and warmer spring temperatures across North America and Eurasia, respectively.
- Ground-based observations supported the variations noted in the satellite data, and association with regional temperature. In North America, three PhenoCam sites showed delayed SOS in 2018 (relative to 2017). In the UK, mean budburst of Pedunculate Oak was delayed by three days in 2018, and the day of spring phytoplankton bloom in Windermere was delayed by six days in North Basin and sixteen days in South Basin in 2018, relative to the 2000-2010 baseline. Relatively cool regional mean spring temperatures in 2018 were associated with these delayed start of season events.