Sidebar 2.S2.2 Phenology of terrestrial and freshwater primary producers

D.L. Hemming[1,2], R. Abernethy[1], C. Armitage[3], K. Bolmgren[4], R. Myneni[5], T. Park[5], A.D. Richardson[6], T. Rutishäuser[7], T.H. Sparks[8], S.J. Thackeray[9].

[1] Met Office, Exeter, UK.
[2] Birmingham Institute of Forest Research, Birmingham University, Birmingham, UK.
[3] Woodland Trust, Grantham, UK.
[4] Swedish University of Agricultural Sciences, Uppsala, Sweden.
[5] Earth and Environment, Boston University, Boston, USA.
[6] School of Informatics, Computing and Cyber Systems and Center for Ecosystem Science and Society, Northern Arizona University, Flagstaff, USA.
[7] Swiss Academies of Arts and Science, Berne, Switzerland.
[8] Coventry University, Coventry, UK.
[9] Centre for Ecology and Hydrology, Lancaster, UK.

Phenology is the study of recurring events in nature and their relationships with climate. The word derives from the Greek *phaínō* 'appear' and *logos* 'reason', emphasizing the focus on observing events and understanding why they occur (Demarée and Rutishauser 2009). Phenological recording has a history that dates back many centuries (Linneaus and Bark 1753; Aono and Kazui 2008). More recently, advances in monitoring technologies have enabled automated and remotely sensed observations, complemented by increasing citizen science participation in monitoring efforts. Phenological information can also be derived from widespread environmental monitoring stations around the globe.

Phenological records clearly demonstrate the biological effects of year-to-year variability in climate, as well as longer-term trends associated with environmental change. Phenological monitoring thus plays an important role in understanding how our planet is changing. Changes in the growing season, for example, are more tangible and more readily conveyed to the general public than seemingly small changes in mean annual temperature.

Here, we describe just a fraction of the phenological information currently available, highlighting northern hemisphere records of phenology of primary producers across a range of spatial and temporal scales.

Ground-based observations

Long-term phenology monitoring network, Germany: Deutscher Wetterdienst (DWD) maintains a dense national phenological observation network and database (http://www.dwd.de/phaenologie/). Plant phenological records dating to 1951, some available since 1925, are openly accessible via the online archive (Kaspar et al. 2014). Currently, about 1100 observers contribute to the database, recording phenological events in cover crops, wild plants and fruit trees. The data have many applications, including advice on current growing season for agricultural activities, pollen forecasts, and environmental change research. Figure 2.S2.1 highlights the record of leaf unfolding of pedunculate oak (*Quercus robur* L.), which has advanced by about 10 days over the last 50 years. This species is referred to as an 'indicator species', and, due to its strong dependence on spring temperature, leaf unfolding is used to mark the beginning of 'full spring'.

Nature's Calendar, UK: Nature's Calendar is a coordinated national 'citizen science' network of phenological observations, supported by the Woodland Trust (https://www.woodlandtrust.org.uk/visiting-woods/natures-calendar/). Currently, over 4000 members of the public contribute regular observations, and the database includes over 2.7 million records, dating from 1695. Early observations of 'Indicators of Spring' were made from 1736 to 1797 by Robert Marsham in Norfolk and continued by his descendants until 1958 (Sparks and Lines 2008). In 1875, a national network was launched by the (Royal) Meteorological Society, which ran until 1948, recording flowering, appearance of bird and insect species, and publishing unusual events and their climate relationships (Clark 1936). In 1998, the Centre for Ecology and Hydrology resurrected this network, and in 2000, was joined by the Woodland Trust to promote phenology to a wider audience (Sparks et al. 1998; Sparks and Smithers 2002). Figure 2.S2.1 highlights the timing of budburst for 4 tree species in this record. As with other plant species, budburst is significantly related to spring average temperature, with a 1°C rise in March or April temperature associated with earlier budburst of 3.5 to 4.8 days, depending on species and region (Abernethy et al. 2017).

Windermere, UK: Seasonal activity of primary producers is monitored in marine and freshwater environments. For example, at Windermere—England's largest lake— fortnightly measurements of chlorophyll-*a* concentrations, a proxy for primary producer biomass, have been recorded since the 1960s. These data show a long-term shift toward earlier spring algal blooms (Figure 2.S2.1), which is correlated with both increasing spring water temperatures as a result of climate change and changes in nutrient availability (Thackeray et al. 2013). Hence, large-scale climatic drivers act alongside more localized lake-specific influences to bring about phenological changes in this system.

Pan European Phenology (PEP) project: The PEP project promotes and facilitates phenological research, education and environmental monitoring across Europe. It maintains the Pan European Phenology (PEP) database (www.pep725.eu), which provides unrestricted data access for science and education. This currently includes 12 million records, with contributions since 1868 from 32 European partners for 46 growing stages and 265 plant species and cultivars (Templ et al. 2018).

Remote sensing

Remote sensing provides some of the clearest records of regional, hemispheric, and global phenological changes by linking radiance measurements to photosynthetic indicators of terrestrial and marine primary producers (Park et al. 2016; Sapiano et al. 2012).

Near-surface remote sensing: Digital camera networks observe ‘the rhythm of the seasons’, from the tropics to the tundra. PhenoCam (http://phenocam.sr.unh.edu) is a collaborative network of over 400 cameras, most at research sites in the United States. Greenness measures (Richardson et al. 2018) derived from camera imagery can be used to track vegetation activity and identify the start and end of season. At one temperate deciduous forest (Richardson et al. 2007), the 2017 growing season was markedly shorter than the decadal average because of late onset and early senescence (Fig. 2.S2.2a). At the same site, the seasonal cycle of canopy greenness follows that of gross primary productivity (GPP) estimated from eddy covariance measurements of CO_2 fluxes, confirming the role of phenology in regulating ecosystem carbon fixation (Richardson et al. 2010; Fig. 2.S2.2b). The difference between this cooler forest and a warmer forest (Fig. 2.S2.2c) illustrates the role of climate in controlling phenology. These data can therefore help improve understanding of relationships between phenology, ecosystem processes, and environmental drivers. Furthermore, phenocam data are valuable for ground truthing satellite observations, as they are continuous in time and require minimal correction or screening for atmospheric effects.

Satellite remote sensing: Satellite-derived phenology indices provide useful regional to global-scale monitoring for phenology studies (Zhang et al. 2003). Fig. 2.S2.3 highlights Northern Hemisphere land surface phenology indices during 2000-2017, derived from radiance observations from the MODIS sensor. It shows a widespread and continued earlier start-of-season (−1.5 days) and later end-of-season (+1.3 days) over this period (Park et al. 2016). In 2017, the start-of-season reveals a dramatic spatial contrast between North America and Eurasia. Northeastern Europe and western Russia showed a striking delay (+6.0 days) associated with an anomalous spring cold spell (−2.4°C), whereas North America showed a widespread earlier start-of-season (−5.1 days), due to warmer than average spring temperatures (+0.5°C). The end-of-season across Eurasia was generally later than average (+2.3 days), but earlier (−3.6 days) over southern European temperate zones.

Many phenological events provide clear indicators of the influence of climate on our environment and natural resources. Current observations apply diverse techniques to monitor phenological changes across wide spatial scales - from global biomes to microscopic organisms. Furthermore, phenology records exist that span multiple decades, even centuries, and these provide valuable archives of long-term environmental change. There is now a fundamental need for integrated analyses of multiple phenology and climate observations to help understand, and prepare for, the future impacts of climate variability and change on environmental systems, and routine monitoring to capture important changes as they occur.

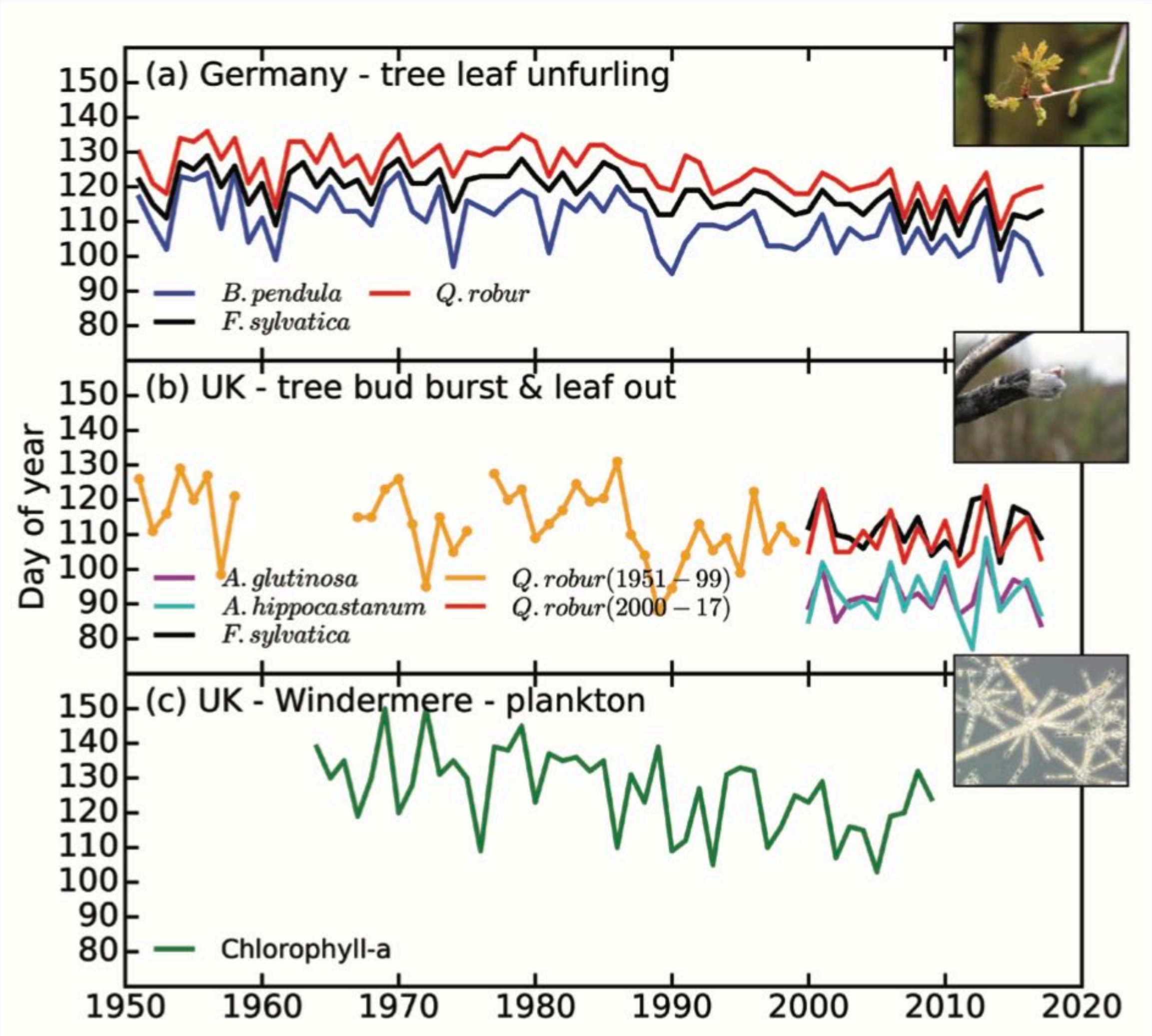

FIG. SB2.5. Time series of phenological changes in primary producers from records in Germany and UK, showing timing (by ordinal date) of (a) leaf unfolding of tree species in Germany from DWD national network: Pedunculate oak – *Quercus robur* L, (b) budburst of 4 common tree species in U.K. from Nature's Calendar: Alder - *Alnus glutinosa* L. Gaertn; horse chestnut - *Aesculus hippocastinum* L.; pedunculate oak; and beech - *Fagus sylvatica* L, and (c) long-term phenological changes in spring phytoplankton growth, indicated by the seasonal timing of maximum spring chlorophyll-*a* concentrations. Original chlorophyll data collected from the north basin of Windermere by the Centre for Ecology & Hydrology and the Freshwater Biological Association, U.K.

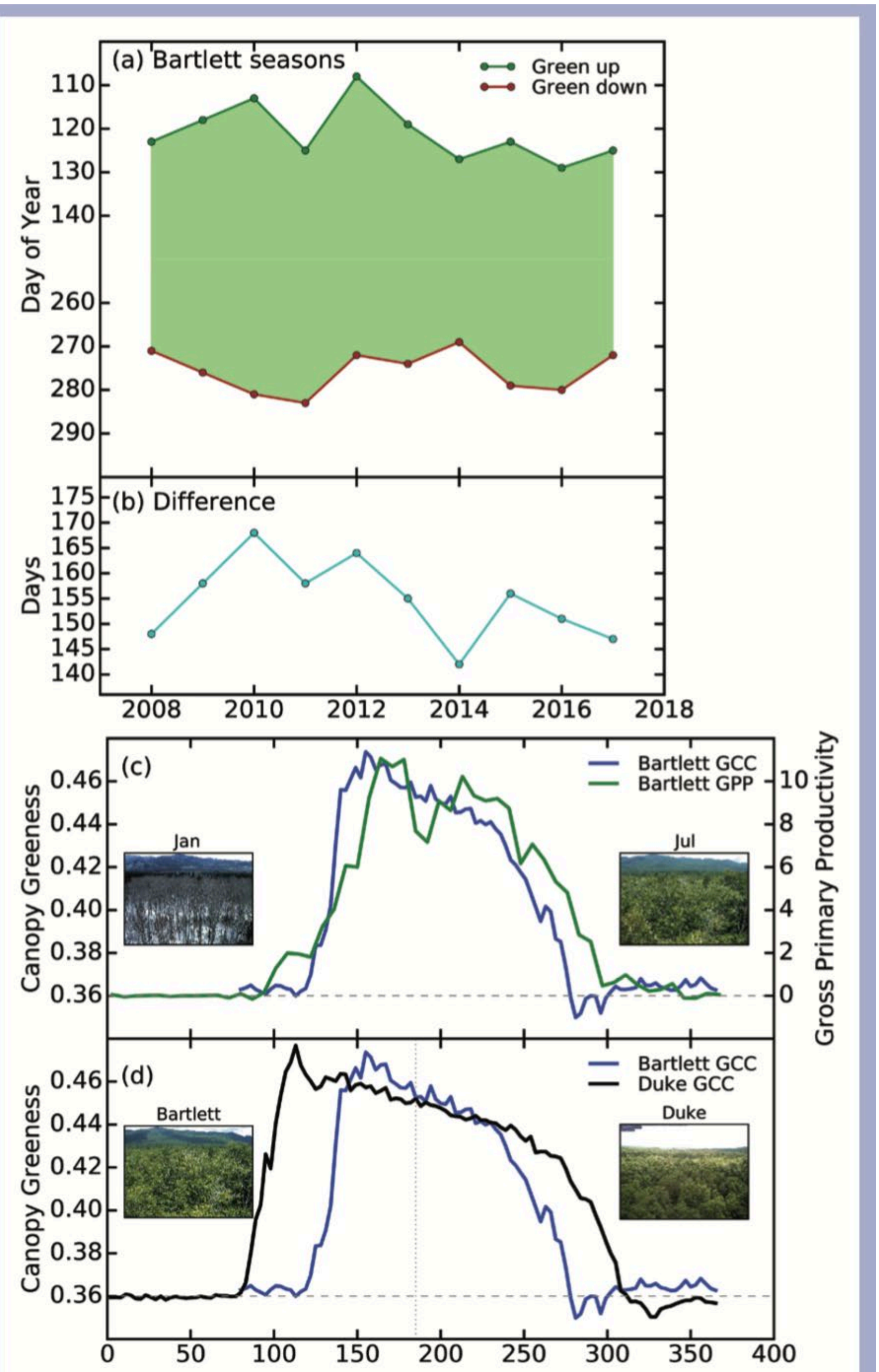

FIG. SB2.6. Phenocam records of canopy greenness (green chromatic coordinate, GCC) and GPP from two deciduous forest sites in the U.S.: Bartlett Experimental Forest, NH, and Duke Forest, NC, showing: (a) Time series of day of year of "Greenup", "Greendown" and (b) number of days of "Green canopy duration" at Bartlett, (c) comparison of seasonality of GCC and GPP (estimated from flux measurements) at Bartlett during 2017, and (d) seasonality in GCC between Bartlett (mean annual temperature = 6.6°C) and a warmer site, Duke (mean annual temperature = 15°C) during 2017. Photos show both sites in Jul 2017.

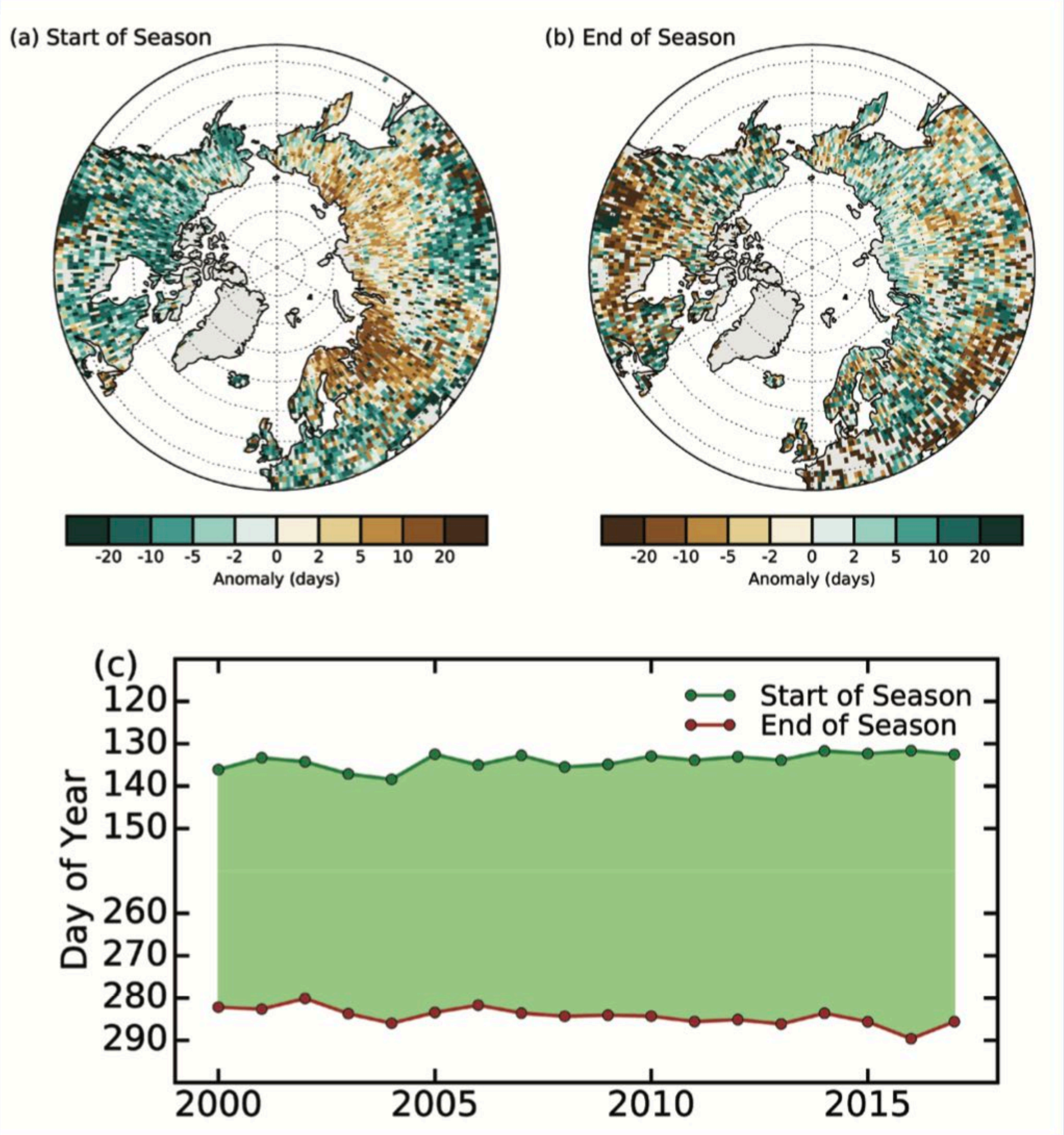

Fig. SB2.7. MODIS-derived NH (>45°N) land surface phenology, showing 2017 anomaly (days), relative to 2000–17 average, for (a) start-of-season, (b) end-of-season, and (c) hemispheric average day of year of the start and end of season for 2000–17.