

Three decades of multi-dimensional change in global leaf phenology

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Changes in the phenology of vegetation activity may accelerate or dampen rates of climate change by altering energy exchanges between the land surface and the atmosphere^{1,2} and can threaten species with synchronized life cycles³⁻⁵. Current knowledge of long-term changes in vegetation activity is regional⁶⁻⁸, or restricted to highly integrated measures of change such as net primary productivity⁹⁻¹³, which mask details that are relevant for Earth system dynamics. Such details can be revealed by measuring changes in the phenology of vegetation activity. Here we undertake a comprehensive global assessment of changes in vegetation phenology. We show that the phenology of vegetation activity changed severely (by more than 2 standard deviations in one or more dimensions of phenological change) on 54% of the global land surface between 1981 and 2012. Our analysis confirms previously detected changes in the boreal and northern temperate regions⁶⁻⁸. The adverse consequences of these northern phenological shifts for land-surface-climate feedbacks¹, ecosystems⁴ and species³ are well known. Our study reveals equally severe phenological changes in the southern hemisphere, where consequences for the energy budget and the likelihood of phenological mismatches are unknown. Our analysis provides a sensitive and direct measurement of ecosystem functioning, making it useful both for monitoring change and for testing the reliability of early warning signals of change¹⁴.

Recent climate change has shifted species distributions^{15,16} and leaf phenology^{17,18} around the world, leading to mismatches in previously synchronized phenological cycles^{3,4}. Such mismatches greatly increase the risk of extinction for affected species, and ongoing climatic and phenological change is expected to further increase this risk⁵. Despite documenting and predicting effects of climate change on many organisms, these previous studies do not provide an easy way of inferring how widespread such changes are or where they are most severe. In addition to being a symptom of climate change, vegetation change also feeds back to the climate system by forcing rates of energy exchange between the land surface and the atmosphere. Changes in the vigour and timing of vegetation activity can therefore accelerate or slow down rates of climate change¹. Yet, the extent to which changes in vegetation phenology will impact the climate system by modifying albedo, transpiration, partitioning between latent and sensible heat in the atmosphere, and cloud formation, has been identified as a major source of uncertainty in climate change projections^{2,19}.

To quantify changes in global vegetation activity, previous studies have used remotely sensed data to quantify changes in primary productivity⁹⁻¹². These studies have indicated an overall increase

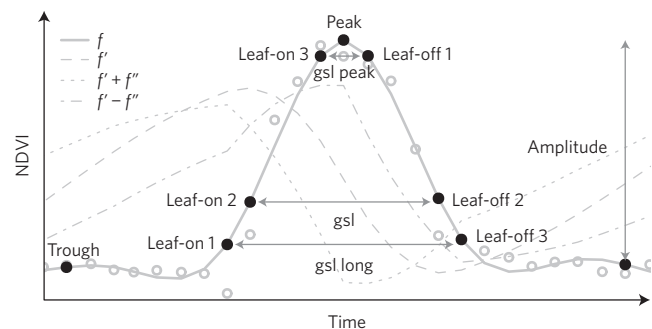


Figure 1 | Calculated phenological metrics. NDVI data for a single phenological year of an illustrative pixel, showing the 21 phenological metrics used in this study. Each labelled point represents a date and an associated NDVI value. The integral of the curve is also calculated. The fitted spline (f), first and second derivatives (f' , f'') were used to calculate phenological metrics. gsl, growing season length.

in net primary productivity (NPP) during the 1980s and 1990s (ref. 9), whereas evidence for a decrease during the 2000s (ref. 11) has been debated²⁰. Although estimating NPP is important for describing carbon sequestration, it is a highly integrated metric that masks important details of the nature of change. For example, it provides no information on the likelihood of phenological mismatches and limited information on consequences for the land-surface energy budget. Consequently, constant NPP does not guarantee that vegetation is not responding to changing climates and increased atmospheric CO₂ in ways that affect the functioning of the Earth system. To quantify intra-annual shifts in the timing and vigour of vegetation activity, remotely sensed absorption of photosynthetically active radiation by the land surface can be used to directly infer photosynthetic activity.

We present a global analysis of change in the seasonal pattern of photosynthetically active radiation absorbed by the land surface as measured by the normalized difference vegetation index (NDVI). We improve on previous analyses that have used NDVI to infer phenological change in two important ways. First, previous studies on long-term changes in leaf phenology have been regional⁶⁻⁸. We analyse the GIMMS_{3g} data, a global record from 1981 to 2012, at 0.083° and 15-day resolution. Second, a problem that has prevented global analyses of phenology is that the information content of phenological metrics is not universal. For example, the onset of the growing season is an informative metric in deciduous forests, but less useful in evergreen forests. We use an improved method to

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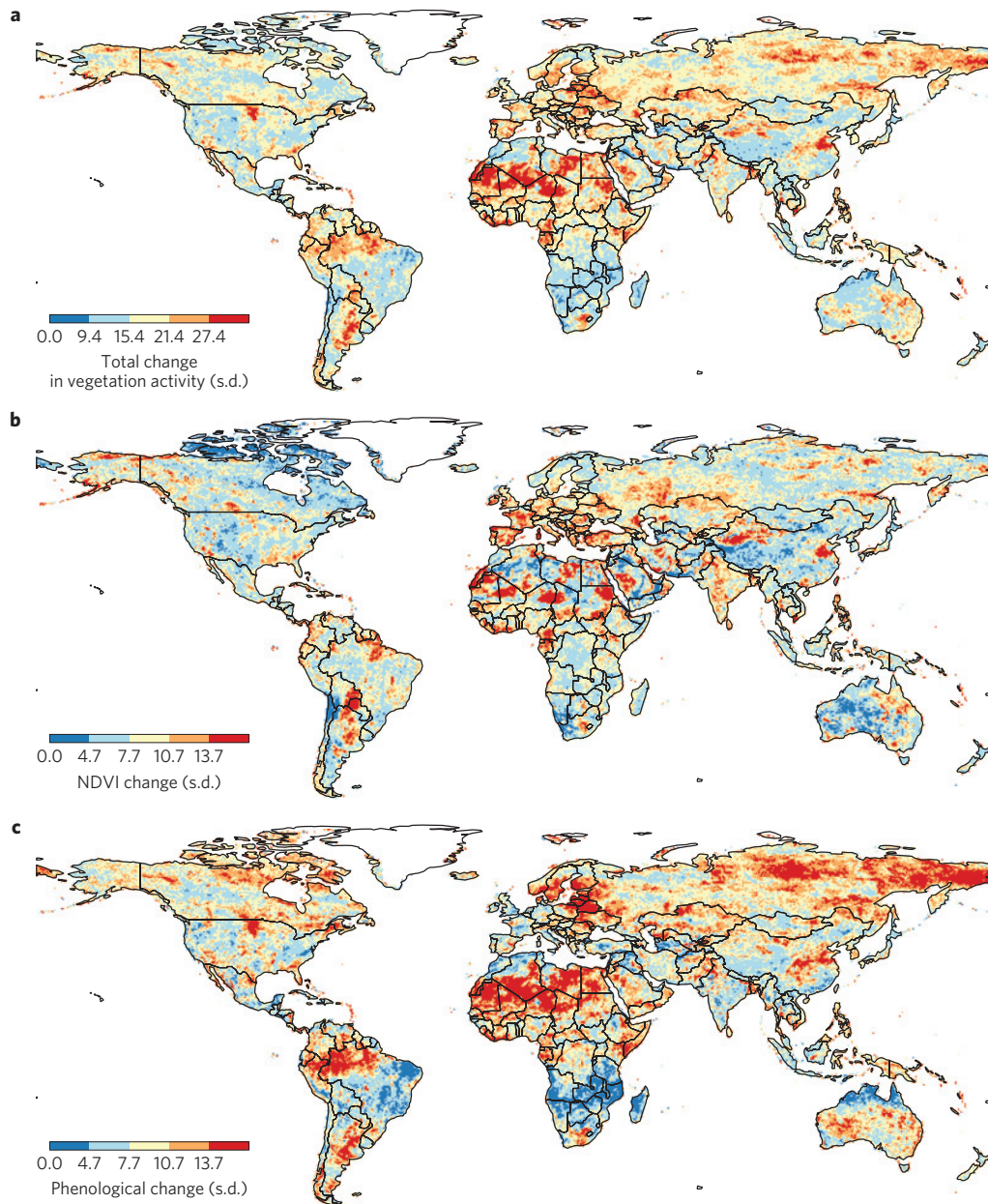


Figure 2 | Phenological change between 1981 and 2012. a, Total change in vegetation activity (the summed change of all 21 metrics). **b**, Change in the vigour of vegetation activity (the summed change of 10 metrics measured in NDVI). **c**, Change in the timing of the phenological cycle (the summed change of 11 metrics measured in days or day of year).

estimate 21 ecologically interpretable metrics of the phenological cycle from the data (Fig. 1) and evaluate the magnitude of change within 83 phenologically similar zones (hereafter called phenomes, shown in Supplementary Fig. 1) to account for the fact that the information content of these metrics differs between ecosystem types. These phenomes were identified using a cluster analysis of the phenological data. To obtain a spatially comparable measure of change, the change per pixel was scaled by the variance of change for the phenome to which it was assigned. Change is therefore reported in standard deviations (s.d.), which can be interpreted as a measure of the severity of change.

We found that leaf phenology changed substantially in most regions of the world, with 95% of the land surface changing by at least 1 s.d. for at least one metric. Figure 2a shows the magnitude of change summed for all 21 metrics. Change was distinctly clustered in space, with relatively large areas where total

change was homogeneous. Splitting total change into changes in the vigour of vegetation activity (NDVI) and changes in timing of the phenological cycle reveals that regions with changes in vegetation vigour are not necessarily associated with changes in phenological timing and vice versa (Fig. 2b,c). For example, the conspicuous change around the Baltic and into Belarus is primarily due to temporal shifts in vegetation activity. Such changes might be associated with increased agricultural yields that have been observed in parts of this region²¹.

The summed changes in Fig. 2 provide a useful summary of phenological change but do not show the complete nature of the change. To further dissect change we therefore grouped the 21-dimensional change into nine general syndromes of change (Fig. 3a). The direction and magnitude of change for each of these nine syndromes of change are summarized in Fig. 3b using plots of the average phenological cycle estimated at the start

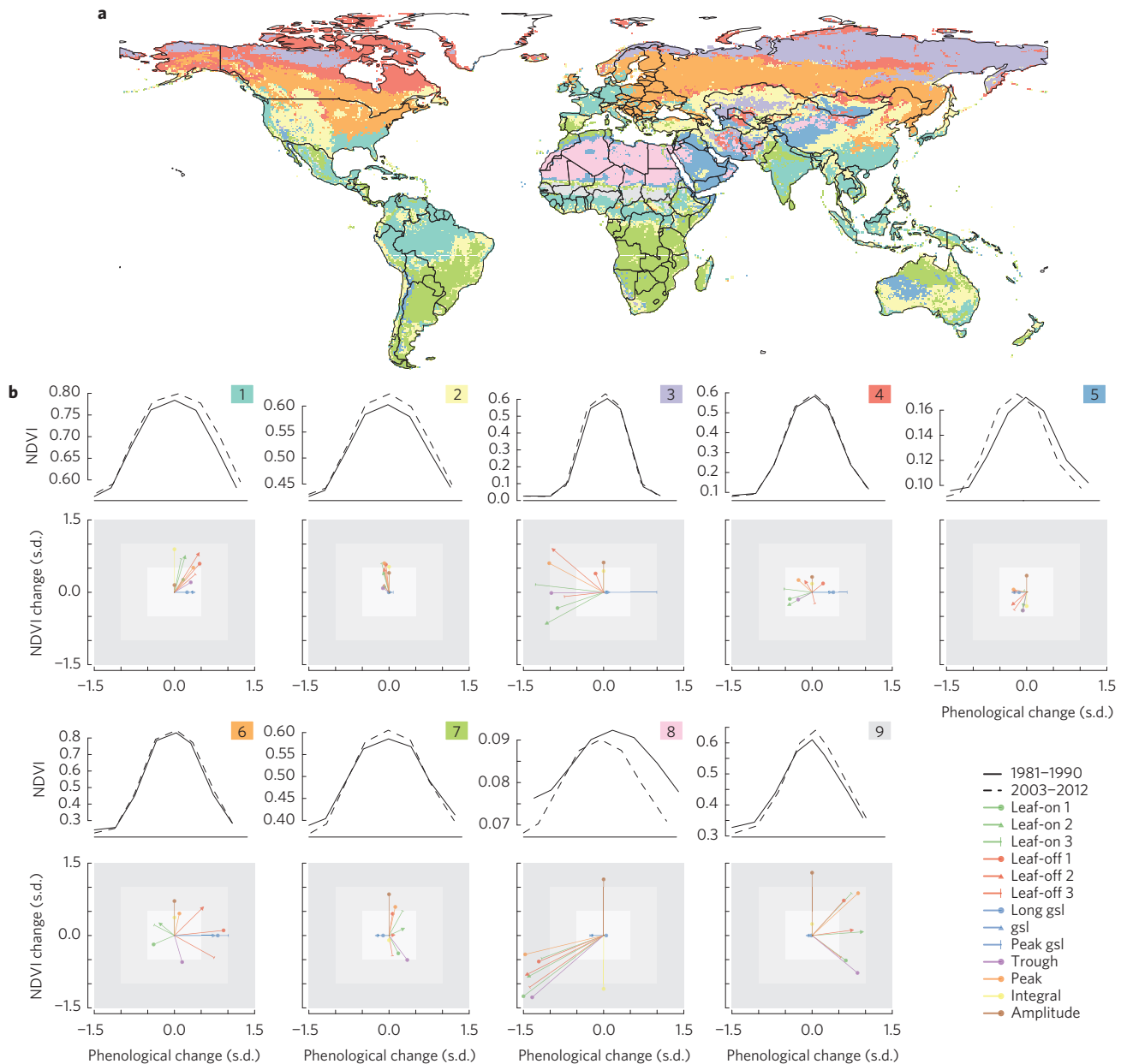


Figure 3 | Syndromes of phenological change. **a**, Global syndromes of change. Map colours correspond to the nine syndrome number labels used in **b**. **b**, For each of the nine syndromes of change, the upper panel shows the average NDVI signal of a phenological year at the start (1981–1990) and the end (2003–2012) of the time series. The bottom panel shows the change between the beginning and end of the time series for all metrics in s.d. The vectors parallel to the axes represent metrics that were originally measured in either NDVI or time units (days, day of year). The angled vectors represent two metrics simultaneously—that is, where an NDVI value was associated with a date.

and end of our time series. We further show in Fig. 3b how, for each syndrome of change, the average of our 21 metrics has changed in s.d. The importance of measuring change relative to the inherent variation in a phenome is illustrated clearly in syndromes 3 and 6, which show a small absolute change, but large relative changes.

In syndromes 3, 4 and 6, which occur in the Arctic and boreal regions, growing seasons have become longer and total photosynthetic activity (NDVI integral) has increased. However, the exact phenological changes that underlie this overall greening differed between regions. In the most northern areas (syndrome 3) the growing season was not only extended, but also occurred earlier owing to both earlier leaf-on and leaf-off dates. Further south (syndrome 4), earlier leaf-on dates extended the growing season,

whereas leaf-off dates did not change. In contrast, still further south (syndrome 6), the growing season was prolonged primarily by later leaf-off dates. The variety of phenological changes we detected in these regions, all of which resulted in net greening, suggests that different mechanisms are driving change in each of these regions.

In contrast to the coherent change over large parts of the boreal region, the nature of phenological change differed markedly over relatively short distances in other regions. This is particularly apparent in West Africa, where five syndromes of change span the region south of the Sahara. Although increases in the peak NDVI and integral of photosynthetic activity that we detected have been previously described in studies reporting greening of the Sahel²² (Syndromes 1 and 9), we found that an extension of the growing season contributed to greening.

In addition to recognizing the distinct phenological shifts that underlie greening in the Arctic, boreal region and Sahel, we identify several areas in South America that have changed severely. The dry Chaco of Paraguay and Bolivia has experienced a drastically reduced NDVI during the dry season (Fig. 2b and Supplementary Fig. 2). In the Espinal and Pampas regions of north-eastern Argentina the growing season has drastically shifted forward and wet-season NDVI has increased. These areas are consistent with areas where linear slopes of NDVI time series changed significantly²³.

Although the described patterns of change are spatially coherent they do not coincide with the distribution of global biomes, which have previously been used to summarize global vegetation change¹³. For example, some savannas in South America, southern Africa and Australia have experienced drastic reductions in dry season NDVI whereas others have not (Supplementary Fig. 2). Therefore, despite having structurally similar vegetation and comparable climates, phenological change is qualitatively different in savannas of different regions, potentially as a result of differences in ecosystem functioning²⁴.

An important conclusion from this study is that qualitatively different phenological changes can lead to quantitatively similar changes in summary variables such as growing season length and total photosynthetic activity, a proxy for productivity. Our estimates of changes in these integrated variables are consistent with more specific studies. We detected a severe change in total photosynthetic activity in, for example, Alaska, Australia, India and the Sahel (Supplementary Fig. 2), consistent with areas that experienced the greatest change in a trend analysis on NDVI time series¹³. We also detected extended growing seasons in the boreal and northern temperate zones (Supplementary Fig. 2), consistent with previous studies in these regions^{6,8}, and higher photosynthetic activity in the Sahel (Fig. 2a), consistent with ref. 22. These agreements indicate that our methodology is sensitive, yet robust enough to be applied globally.

Our methodology also addresses disagreement between previous studies. For example, White *et al.*⁷ reported no changes in the start of the growing season in North American Arctic and taiga, whereas Zhou *et al.*⁸ inferred earlier leaf-on dates from the same data set. Consistent with White *et al.*⁷, our 'leaf-on 1' metric did not change, whereas our 'leaf-on 2' and 'leaf-on 3' advanced by 0–10 days throughout the North American Arctic and the eastern part of the taiga, consistent with Zhou and colleagues⁸. This suggests a change in the shape of the green-up part of the phenological curve. Such differences have previously been ascribed to methodology, prompting White *et al.*⁷ to compare ten different methods of calculating the start of the growing season and advocating an ensemble approach. Our analysis reconciles the apparent discrepancies between White *et al.*⁷ and Zhou *et al.*⁸ by revealing multiple, ecologically distinct, components to the green-up part of the phenological curve.

Our study confirms the boreal and temperate regions of the northern hemisphere as areas of rapid phenological change^{6–8}. In northern regions, long field observational records have been used to attribute these phenological changes to warming climates¹⁷. It has been shown that the resulting mismatches in phenological cycles disrupt trophic interactions and increase extinction risk^{3–5}, and impacts on the land-surface energy budget have been assessed as significant^{1,2}. We detected equally severe changes over large regions of Africa, South America and Australia that have previously gone unnoticed but might have significant ecological and atmospheric consequences. In these regions, field observational records are scarce and leaf phenology is largely driven by precipitation²⁵. As precipitation projections are more uncertain than temperature projections²⁶, the potential for phenological mismatches and consequences for the land-surface energy balance in these regions are highly uncertain. Therefore, analyses of remotely sensed time series of photosynthetic activity are an important and necessary first

step in identifying where vegetation might be responding to changes in climate, atmospheric CO₂ and other atmospheric forcings.

Attributing phenological responses to any of these drivers will require regional approaches, because studies^{17,18,25} suggest that vegetation activity is co-limited by several environmental factors and the limiting factor is likely to be region specific. For example, in African savannas, where rainfall is widely assumed to limit vegetation activity, it has been shown that rainfall does not control leaf onset of all species²⁵. In Europe there is a strong temperature control over leaf onset, but not leaf senescence¹⁷. In a North American grassland, experimental evidence suggests that warming coupled with increased atmospheric CO₂ delays leaf senescence, but that increased CO₂ does not trigger earlier leaf emergence¹⁸. Because CO₂ influences the water-use efficiency of plants²⁷, we expect that increased CO₂ is most likely to extend the growing season where the beginning or end of the growing season is moisture limited. Increased photosynthetic activity over Botswana and north-east South Africa are suggestive of a CO₂ effect²⁸, although how CO₂ interacts with climate and disturbance needs to be considered²⁹.

In conclusion, we show that the majority of the Earth's land surface has, between 1980 and 2012, undergone some form of change in the seasonal pattern of vegetation activity. Our analyses provide a map of where the risk of phenological mismatches is higher and a basis for modelling the radiative forcing consequences of phenological change. The direct measurements of change used here might also serve to monitor change and evaluate the performance of early warning indicators of imminent catastrophic change in ecosystem state.

Methods

Data. We used the GIMMS_{3g} data set (downloaded from <http://ecocast.arc.nasa.gov/data/pub/gimms/3g>), which provides Advanced Very High Resolution Radiometer (AVHRR) NDVI data. The data are 15-day maximum-value composites from 1981 to 2012 at 0.083° resolution. Compositing reduces atmospheric effects (clouds, aerosols) and data have further been processed to reduce effects of navigation errors, major volcanic eruptions and orbital drift of older satellites, and have been subjected to several sensor calibration steps. Finally, a rigorous analysis was carried out to resolve remaining discrepancies between data from different generations of AVHRR sensors³⁰. Data quality scores were provided for each observation.

Defining phenological metrics. Data for each pixel were smoothed using a cubic spline function, which was weighted by data quality scores. A spline, unlike a parametric function, maintains a high fidelity to the data while retaining continuous first and second derivatives. We designed a two-step method to flexibly define the start of the time series for each pixel. First, the average Julian day of minimum NDVI (trough day) was calculated for each pixel using the 31-year time series. In the second step, the exact trough day for each phenological year was determined within a 180-day window (90 days on either side) around the 31-year mean trough day.

The period between two consecutive trough days constitutes a phenological year. For each phenological year 20 additional metrics were extracted (shown in Fig. 1). Instead of defining the 'start of the season' and 'end of season' as a single date, we calculated three dates for start and end of season, which improved our ability to detect change. For example, in some deciduous forests, invasive understory plants extend the growing season by retaining leaves longer than native forest trees³¹. Such change is difficult to describe with a single metric—that is, a large decrease in NDVI still occurs when the trees drop their leaves while the understory plants will cause low NDVI to persist for longer. 'Leaf-on 1', 'leaf-on 2', and 'leaf-on 3' represent the first increase, the fastest increase, and end of increasing (that is, the start of peak) photosynthetic activity, respectively. These dates can be interpreted as leaf emergence, rapid leaf expansion, and attainment of a full canopy. Similarly, three leaf-off dates were calculated and the number of days between leaf-on and leaf-off dates represented three measures of growing season length: 'gsl-long', 'gsl', and 'gsl-peak'.

We calculate the three leaf-on and leaf-off dates using the first and second derivatives of the spline function. For smooth functions—for example, a sine—the maximum of the second derivative indicates when the function starts going concave up, and could hence be used to define the start of the growing season. However, NDVI data is not always smooth and sometimes produces a spline with multiple peaks within a phenological year. Instead of sacrificing accuracy by smoothing the data further, we centred and scaled both the first and

second derivatives, summed them, and calculated the days at which this sum is maximal and minimal (shown in Fig. 1). This method selects for the maximum (or minimum) in the second derivative that is closest to the maximum (or minimum) in the first derivative and provided a robust way of defining the three leaf-on and leaf-off metrics.

This procedure yielded a 31-year time series of 21 phenological metrics for 2,075,445 pixels.

Phenological change over time. For every pixel, change for each of the 21 metrics was defined as the difference between averages of the beginning and the end of the time series—that is, between 1981–1990 and 2003–2012. Trend analysis was avoided as there was no reason to assume a priori that change should be linear or monotonic. Comparing ten-year averages buffers against effects of anomalous climatic events in a single year on the change estimate.

Comparing change spatially. As explained in the text, we scaled the change of each pixel by the variance of phenologically similar regions to obtain a spatially comparable measure of change. Because existing land cover classifications based on the biome concept did not adequately summarize phenological variation, we used a model-based clustering method to identify the optimal number of phenologically similar regions (phenomes). The procedure resulted in 83 phenomes (clustering details are given in the Supplementary Information).

Summarizing change. The final step in our analysis was to summarize change globally, by grouping phenomes with similar type and magnitude of change into nine syndromes (Fig. 3a) using unsupervised hierarchical clustering (details are given in the Supplementary Information). For each syndrome, average change in s.d. was plotted along two axes, one representing change in NDVI, the other representing phenological change (that is, change in dates or number of days; Fig. 3b). The full workflow of our analysis is summarized in Supplementary Fig. 4.

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Author contributions

R.B. and S.I.H. designed the study and data analyses. R.B. performed the analyses with assistance from L.R. R.B. wrote the manuscript with assistance from S.I.H. All authors discussed and commented on the manuscript.

Additional information

Supplementary information is available in the online version of the paper. Reprints and permissions information is available online at www.nature.com/reprints. Correspondence and requests for materials should be addressed to R.B.

Competing financial interests

The authors declare no competing financial interests.