RESEARCH ARTICLE

Methods in Ecology and Evolution | BRITISH ECOLOGICAL SOCIETY

Using archived television video footage to quantify phenology responses to climate change

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Funding information
H2020 European Research Council, Grant/Award Number: 614839 and 757833

Handling Editor: Satu Ramula

Abstract

1. Predicting how the timing of cyclic life-history events, such as leafing and flowering, respond to climate change is of paramount importance due to the cascading impacts of vegetation phenology on species and ecosystem fitness. However, progress of this field is hampered by the relative scarcity, and geographic and phylogenetic bias, of long-term phenology datasets.

2. By taking advantage of archived television video footage, we here developed an innovative tool using previously unexploited records to build long-term datasets of phenological responses. To demonstrate the potential of this method, we worked with broadcast archives of sport events and focus on one of the most famous professional road cycling races world-wide, the Tour of Flanders.

3. After viewing >200 hr of film, we compiled 523 individual × year observations of leaf-out and flowering of 46 individual trees and shrubs visible in four decades (1981–2016) of video footage. We detect surprisingly strong advances in the timing of tree leaf-out and flowering in the footage: trees almost never had flushed at the time of the spring race in the 1980s while significantly more individuals had flushed in the video footage between 2006 and 2016 (probabilities of leafing and flowering increased by 19% and 67%, respectively). These shifts were most strongly related to January–March temperatures and growing-degree hours (cumulative heat) in the preceding months.

4. We demonstrate that this technical advance offers key benefits to fill gaps in existing phenology time series and reveal that archived video footage can indeed be applied to determine species-temperature relationships with high spatiotemporal resolution. Only by compiling more data from the past will we be able to further our understanding on the effects of climate change on species and ecosystems in the future.

KEYWORDS
climate change, flowering, herbarium specimens, leafing, phenology, television archive, trees

1 | INTRODUCTION

Contemporary climate change is affecting the distribution and functioning of vegetation across the globe (Peñuelas et al., 2013). As a result of climate change, plants also alter their phenology, that is the timing of cyclic life-history events such as leafing, flowering and fruiting. It is one of the key outstanding issues in ecology and evolution to better quantify and predict phenology changes in response to

altered temperatures and precipitation patterns (Wolkovich, Cook, & Davies, 2014). Plant phenology responses are at the heart of climate change impact assessments because shifting vegetation phenology can not only affect plant fitness and community composition (e.g. via altered species interactions such as competition for resources or mismatches with pollinators), but also impact ecosystem processes such as primary production, nutrient cycling, carbon sequestration and radiation budgets via albedo effects (Chuine, 2010; Peñuelas et al., 2013). The spatial, temporal and phylogenetic bias of the available phenology data, however, limits progress of this field and innovative tools to compile new phenology databases are urgently needed (Willis et al., 2017).

The most commonly used empirical methods to study how plants temporally track climate change take either advantage of long-term observations or experimentally manipulate climate in small field plots. First, long-term in situ observations of plants' phenophases in private and botanical gardens, parks and natural ecosystems can be related to historical climate data. Yet, this approach requires long-term datasets which are relatively rare, often focused on a limited set of "popular" taxa (e.g. wildflowers, fruit trees, common forest trees and shrubs) and biased towards temperate regions on the northern hemisphere (see for instance, Prevey et al., 2017; Rafferty & Nabity, 2017; Sparks & Carey, 1995; Thackeray et al., 2016; Wolkovich et al., 2012). A second oft-applied approach is to experimentally expose plant communities to warmer temperatures in small field plots with devices such as open-top chambers, infrared heating lamps and heat resistance cables (Aronson & McNulty, 2009; De Frenne, 2015). Nonetheless, with few exceptions, many of these experiments only cover a few years (Wolkovich et al., 2012, 2014).

To address the relative scarcity of reliable long-term monitoring data, we here developed an innovative, unexploited tool by taking advantage of archived television video footage to assess decades-long phenological responses to climatic cues. This method is comparable to the use of legacy data such as herbarium and museum specimens, old logbooks and repeat photography (Kwok, 2017; Miller-Rushing, Primack, Primack, & Mukunda, 2006; Munson & Long, 2017; Primack & Miller-Rushing, 2009; Vellend, Brown, Kharouba, McCune, & Myers-Smith, 2013; Willis et al., 2017). Yet, archived video footage from, for example news items, sport events, demonstrations or pop concerts, offers key complementary advantages to test for effects of climate change on plant phenology. To establish the potential of this method, we here focused on broadcast archives of sport events (professional cycling races broadcast worldwide). Several professional cycling races, such as Milan-San Remo, the Tour de France, the Tour of Flanders or Liège–Bastogne–Liège, are broadcasted annually across the globe and these recordings are stored in television archives world-wide (see http://fiatifta.org/). Second, major cycling races are organised annually on public roads (which is an exception for sport events) with the first editions already organised in the beginning of the 20th century. This potentially leads to long time series. Third, video footage concerns moving images thereby often offering different angles of vision of one standardized location, even within 1 year. Exactly the lack of standardization of location and angle of vision is an important drawback of the application of repeat photography in ecological research (Vellend et al., 2013). Fourth, many cycling races are organised in the spring, an important phenological period, and have relatively fixed routes, climbs and sites of start and finish allowing us to study plant individuals that feature annually in the video footage on these locations. Finally, cycling races cover almost the entire globe: although most races with a long tradition are held in Europe, they are now organised throughout the world thereby potentially decreasing geographic biases, at least in the long term. These important advantages allow us to quantify phenology and performance of plants with high spatiotemporal resolution using standardized protocols.

To establish and thoroughly test this tool, we here focus on leaf-out and flowering of long-lived woody plants (trees and shrubs) growing along the route of the Tour of Flanders in Belgium. This is one of the oldest professional cycling races of the globe with the first edition organised in 1913 and archived video footage available since 1929. We accessed almost four decades of video footage of this race (recorded from 1981 to 2016) and quantified timing of leaf-out and flowering of 46 individual trees and shrubs resulting in 523 individual × year combinations. We specifically evaluated the potential of using broadcast archives in global-change research by addressing the hypothesis that leafing and flowering of trees has advanced due to warming temperatures.

2 | MATERIALS AND METHODS

2.1 | Study area

To quantify the timing of leafing and flowering of woody plants over time, video footage of the Tour of Flanders was used. The Tour of Flanders is a major annual road cycle race in Belgium, held every spring around early April (Figure 1a and Supporting Information Figure S1). The cycling race is part of the UCI World Tour with the best professional cyclists of the world and is one of the five "monuments" (see also Vekeman, Meulders, Praet, Colpaert, & Van Puyenbroeck, 2015; Versichele, Neutens, Goudeseune, van Bossche, & van de Weghe, 2012). The event started in 1913, with interruptions between 1915 and 1918 due to World War I, and celebrated its 100th edition in 2016. Archived video footage of the race is available since 1929. We used the broadcast archive of the Flemish Radio and Television Broadcasting Organization (VRT) for the present study and focused on the four most recent decades (the period 1981–2016) because of the availability of higher quality colour film. After comparing the different routes of these 36 editions, 12 frequently occurring climbs were picked as reference points (Figure 1a). These climbs more often feature in the available video footage and act as landmarks.

2.2 | Archive work and quantifying tree phenology

The archive work was performed in Avid Interplay Media Asset Manager Desktop (www.avid.com). Images of the trees occurring

(a)

(b)

(c)

FIGURE 1 Overview of the study area and the 12 selected climbs of the Tour of Flanders (a) and the tree phenology scoring system based on the video footage (b,c). Shown in (b) is a still based on the video footage of birch trees (*Betula pendula*) on one of the selected climbs (Paterberg, tree ID 32 from Supporting Information Table S1) showing the applied phenology scoring system from 0 (left) to 4 (right). (c) Example of a time series of stills from the video footage from tree ID 30 (*Populus × canadensis*, Supporting Information Table S1) with 21 years of data between 1988 and 2014. The phenology scores per year for this given tree are between brackets. The analysed tree is indicated by the white dashed line. Copyright photos: Flanders Classics

on or around the 12 selected climbs were processed for each year where the tree was clearly visible in the recorded film. After viewing >200 hr of film, which represented the bulk of the work, a database of 46 different trees and 523 images of these trees was compiled (cf. Figure 1c for an example). Subsequently, every image of a tree × year replicate was given a phenology score between 0 and 4 based on the images (Figure 1b): 0: none of the leaves/flowers had flushed already at the time of the race and no leaves/flowers were visible; (a) 1%–25% of the maximal amount of leaves/flowers visible; (b) 26%–50% of the maximal amount of the leaves/flowers visible; (c) 51%–75% of the maximal amount of the leaves/flowers visible; (d) almost all leaves/flowers flushed, 76%–100% of the maximal amount of the leaves/flowers visible. Quantifying the phenology scores after the extraction of the individual tree images from the video footage required only a few

additional hours of work. For all further analyses, trees that had a phenology score of 0 in all observation years were not further considered. This resulted in a final database of 288 images of 24 tree individuals: 238 images of 20 individuals concerned leafing phenology and 50 images of 4 individuals concerned flowering phenology (Supporting Information Table S1).

2.3 | Climatic data

To couple phenology scores to the past climate, the best available gridded temperature and precipitation data for Belgium were used, with high spatial resolution (Delvaux, Journee, & Bertrand, 2015). Weather station based daily maximum and minimum temperatures and daily precipitation amounts were used for the modelling. Data quality control procedures were first applied to

ensure that only valid measurements were involved in the gridding process. Afterwards, the set of unevenly distributed temperature and precipitation data was interpolated using kriging on a 4 × 4 km² regular grid over Belgium (Delvaux et al., 2015; Wackernagel, 1995). From this model, we extracted tree-specific data for maximum and minimum temperature (in °C) and precipitation amounts (in mm/day) from January 1, 1979 to December 31, 2016. The mean daily temperature (in °C) per day was approximated by calculating the average of the daily maximum and minimum temperature.

Based on these climate data, six different temperature metrics were calculated per tree and year and related to the tree phenology: the mean annual temperature, the mean temperature between January 1 and March 31 (further referred to as "JFM temperature"), the mean temperature between January 1 and the year-specific date of the cycling event, the mean temperature between October 1 and December 31 of the previous year (further referred to as "OND temperature of the previous year"), the cumulative growing-degree hours (GDH) of the whole year, and, finally, the cumulative GDH from January 1 till the date of the cycling event. GDH were calculated according to Lindsey and Newman (1956). In addition to the six temperature metrics, two precipitation metrics were calculated as well: the total precipitation between January 1 and March 31 (referred to as "JFM precipitation") and the mean precipitation between October 1 and December 31 of the previous year (referred to as "OND precipitation of the previous year"). These eight temperature and precipitation metrics were chosen to represent key weather variables, time windows (annual, spring, autumn) and aggregate statistics (Van de Pol et al., 2016) that affect phenology. For instance, spring temperatures and GDH have been shown to be very accurate to predict flowering (Diekmann, 1996).

2.4 | Current environmental characteristics of each tree

In addition to the climate data, current characteristics of the trees visible in the video footage, as well as their abiotic and biotic environment, were assessed during field visits in September–October 2016. In contrast to the climate data, these data are more difficult, or impossible, to hindcast, and thus, no historical data were available for these characteristics. Yet, it is still useful to include the recent field data due to potential effects on among-individual phenological changes.

2.4.1 | Tree characteristics

The following characteristics were determined: species, height, crown size and diameter at breast height (DBH), defoliation and discoloration. Tree height was determined with a Vertex IV (Haglöf). The ground-projected tree canopy crown size and the diameter of the tree trunk at breast height (DBH) were also measured. A vitality score was given by visually estimating the percentage of defoliation and discoloration of the foliage of each tree (following UNECE ICP Forests Programme Coordinating Centre, 2016).

2.4.2 | Environment

Characteristics of the environment were also assessed: latitude and longitude, the land use with respect to the position of the tree (garden, meadow, roadside, edge of a forest) and surroundings within a 25-m radius (meadow, arable land or paved), slope and aspect, and soil characteristics. Within a 25-m radius around the focal tree, the number of other trees and their percentage of canopy cover were calculated. The distance to the nearest tree was measured and the slope and aspect determined with a level tool and compass, respectively. For each tree (unless this was impossible due to access restrictions or paved surroundings), a soil sample (20 cm depth) was taken with the use of a soil auger. The samples were dried to constant weight at 40°C for 48 hr, ground and sieved over a 2 mm mesh and analysed for pH-H_2O, phosphorus (P), carbon (C) and nitrogen (N). Samples were analysed for pH-H_2O by shaking a 1:5 ratio soil/H_2O mixture for 5 min at 300 rpm and measuring with a pH meter Orion 920A with pH electrode (Ross sure-flow 8172 BNWP; Thermo Scientific Orion). Bioavailable P which is available to plants within one growing season was determined by extraction in $NaHCO_3$ (P-Olsen; according to ISO 11263:1994(E)) and colorimetric measurement according to the malachite green procedure. For total C and N, the samples were combusted at 1,200°C and the gases measured in a thermal conductivity detector in a CNS elemental analyzer (vario Macro Cube; Elementar, Germany).

2.5 | Data analyses

All analyses were performed in R (R Core Team, 2017). Standard deviations of the phenology scores (an ordinal response variable) over particular time periods were calculated by bootstrapping 999 times using the *boot*-function in the BOOT-package (Canty & Ripley, 2017). Relationships between the phenology score and climatic and other biotic and abiotic environmental variables were analysed by fitting Bayesian generalised linear mixed models using Markov chain Monte Carlo techniques with ordinal data using the *MCMCglmm*-function in the MCMCGLMM-package (Hadfield, 2010). This was done separately for leafing and flowering phenology, and one predictor variable at a time because of multicollinearity (Supporting Information Table S2). To account for the repeated measurements of the phenology of the same tree over time, the tree was used as random-effect term. We used 100,000 iterations after a burn-in of 5,000, ran three independent chains to check for model convergence and used the following priors: for B, parameters $\mu = c(0, 0)$, $V = \text{diag}(2) \times 1e10$, for R, parameters $V = 1$ and fix = 1, and for G, parameters $V = 1$ and $\nu = 0.002$. Finally, we performed three types of sensitivity analyses. First of all, a sensitivity analysis of the *MCMCglmm* results was performed by comparing MCMC outputs to alternative modelling approaches (results available in Supporting Information Table S3): (a) as arcsine sqrt-transformed

mid-point percentages analysed with linear mixed-effect models with Gaussian error distribution (following Warton & Hui, 2011) and (b) as integer phenology "counts" with generalised linear mixed-effect models with Poisson error distribution. A second and third sensitivity analysis was performed against the assigned phenology scores (by randomly reclassifying these by one unit) and MCMC priors (Supporting Information Appendix S1). However, all these methods resulted in similar findings illustrating that the emerging patterns are robust to the statistical method used.

3 | RESULTS AND DISCUSSION

Temperatures across the 12 analysed climbs increased by c. 1.5°C since 1980, while precipitation did not show a directional trend. Annual GDH also significantly increased by almost 10,000°C hour

since 1980 (Supporting Information Figure S2). As a response to these changes in the climate system, we detect surprisingly strong shifts in the phenology of leaf-out and flowering of trees in the historical video footage over four decades. In the leafing dataset, 129, 39, 24, 24 and 22 images were classified into phenology category 0, 1, 2, 3 and 4, respectively. In the flowering dataset, the corresponding numbers were 24, 1, 1, 3, 21 images. However, a strong temporal shift is evident: trees almost never had leaves at the time of the spring race in the 1980s (mean phenology score of 0.24 ± 0.19 bootstrapped *SD* on the day of the race between 1981 and 1990, and only zeroes occurred before 1987) while leaf-out and flowering occurred significantly earlier (mean phenology score of 1.45 ± 0.17 bootstrapped *SD* on the day of the race) in the decade between 2006 and 2016 (Figure 2a,b). Thus, the probability of obtaining a score higher than 1 (i.e. at least >25% of the leaf or flower buds had flushed) increased from 0% to 67% for
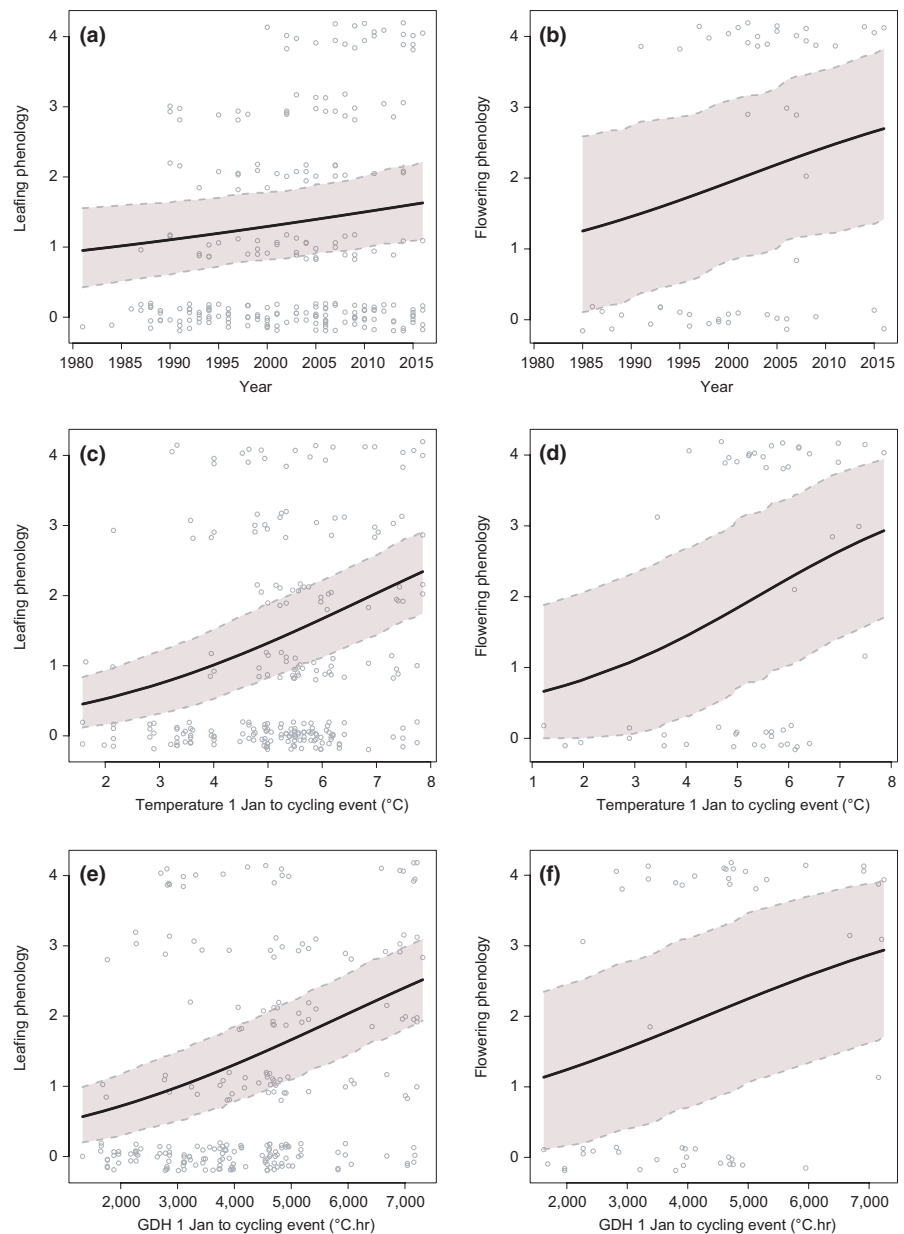
FIGURE 2 Effects of the year and temperature variables on leafing (a,c,e) and flowering phenology (b,d,f). Note that individual grey points of the phenology scores are ordinal integers between 0 and 4, but these data have been jittered along the *Y*-axis for clarity. The black line and shaded polygon represent the mean fit and 95% credible intervals of the generalised linear mixed models using Markov chain Monte Carlo techniques. Because of multicollinearity, predictors were tested one by one in these models. More details on the statistical results are available in Supporting Information Table S3

flowering and from 26% to 45% for leaf-out between 1981–1990 and 2006–2016, respectively.

Climatic variables related to temperature and accumulated heat (GDH) most strongly explained this temporal trend; phenology scores of both leafing and flowering significantly increased in years with higher JFM temperatures and GDH (Figure 2c–f and Supporting Information Table S3). The variables that enhanced development of leaves and flowers most positively were the mean JFM temperature (January–March) and the mean temperature and GDH between January 1 and the date of the cycling race. This underpins the importance of the preceding months for species' phenology (Menzel et al., 2006). On the other hand, OND temperature from the preceding year (October–December), precipitation and other environmental characteristics such as the characteristics of the soil, tree and surroundings had no significant effects on the phenology (Supporting Information Tables S3 and S4). Of all the tree characteristics, crown width had the largest effect on the phenology scores (although this effects was not significant), with taller trees displaying delayed phenology, an effect also observed in other species (Supporting Information Table S4; Vitasse, Lenz, Hoch, & Körner, 2014). While precipitation did not affect phenology in our study in a temperate ecosystem, rainfall can be of (some) importance to phenological events of plants growing in, for example Mediterranean ecosystems (Gordo & Sanz, 2010).

Using time series and experiments, numerous species have been shown to advance their phenology: using long-term observations, species show a mean sensitivity of *c.* 2.5–3 days per decade or *c.* 5 days per degree warming (Menzel et al., 2006; Parmesan, 2007; Wolkovich et al., 2012). Results from short-term experiments are more ambiguous with some species actually showing no shifts or even delaying the timing of their life events in response to warming temperatures (Munson & Long, 2017; Sherry et al., 2007; Thackeray et al., 2016; Wolkovich et al., 2012). Our approach also makes it possible to calculate species-specific responses to climate change, including for more recently introduced (ornamental) species for which few phenology time series are available such as *Magnolia* sp. and *Forsythia* sp. (e.g. Roetzer, Wittenzeller, Haeckel, & Nekovar, 2000). Such data can be of importance for, for instance, horticulturalists. To demonstrate the possibility of this approach, we calculated sensitivities for hornbeam (*Carpinus betulus*) and detect a high temporal and temperature sensitivity of 4.7 days per decade and 12.2 day/°C respectively (Supporting Information Appendix S2). The species most responsive to warming air temperatures in our study were predominantly early unfolding species including *Crataegus monogyna* and *Carpinus betulus* for leaf expansion and *Magnolia* sp. for flowering (Figure 3). However, leaf bud burst of a late-successional, late leaf-out species such as *Fagus sylvatica* was also positively correlated with warming temperatures (Figure 3). Species such as *Pyrus communis*, *Salix* sp. and *Fosythia* sp. (with possibly many different varieties and genotypes) did not respond significantly to any of the measured climatic variables. Phenology of, at least long-lived late-successional trees, is probably more dependent on the photoperiod and chilling requirements (Körner & Basler, 2010). This divergence between

earlier and later species corroborates previous observational findings from time-series analyses (Menzel et al., 2006; Zhang, Yuan, Liu, & Dong, 2015).

The use of archived video footage is an additional, complementary source of legacy data to obtain historic phenology data across species' ranges, in addition to those obtained from long-term observations, repeat photography, old logbooks, herbarium records and citizen science projects (Kwok, 2017; Vellend et al., 2013; Willis et al., 2017). To exemplify this, we correlated our phenology scores to phenology observations using ground-based observational methods in *Betula pendula* between 2001 and 2016, and detected significant correlations between both methods (Supporting Information Appendix S3). Valuable video footage is certainly not limited to those of cycling races: archived video from other sport events such as golf and rally races, news items, demonstrations, pop concerts and even CCTV cameras might be useful on the condition that the study object appears repeatedly on screen. One of the key advantages of the use of archived video footage is that one can easily select the phenophase (leaf bud burst, flowering, fruiting, senescence, etc.), species and ecosystem of interest, also when these phenophases, species and ecosystems were unstudied in the past. The only condition is that the study object occurs close enough to the camera, and features regularly in the recordings. Increasing efficiency via automation of data extraction from the video footage to scale up to more locations or individuals is likely also possible via green pixel recognition and (semiautomatic) georeferencing such as used for precision agriculture (Romeo et al., 2013).

There are numerous possibilities within the field of global change biology in which analyses of video footage such as reported here can deliver empirical high-quality data. Shifts in leaf and flower unfolding dates may be quantified in high spatiotemporal detail as demonstrated in this study. Our approach as exemplified here is easily extendable to test for effects of climate change on, for instance, phenology of understudied species (e.g. introduced plants which are less monitored in traditional time series), sowing and planting dates of agricultural crops, and urban versus rural phenology (Li et al., 2017). In addition, archived video footage makes it possible to quantify species distribution range shifts, for example by georeferencing locations and calculating the annual spread of both native and introduced species visible in the footage. Such an analysis was recently also performed by using geolocated Google street view imagery (Hardion, Leriche, Schwoertzig, & Millon, 2016). Plant fitness (e.g. by assessing defoliation, discoloration, fruit number, occurrences of visible pests and pathogens) and processes at the landscape scale such as land-use changes, forest management and landscape phenology (sensu Thackeray, 2016) can also be considered. Applications outside the field of global change biology are also possible, such as temporal monitoring of water levels of rivers and lakes.

As with any other approach, specific methodological disadvantages are associated to this technique. First of all, especially for the older (black and white) film, the video resolution may turn out to be insufficient. Yet, image quality appeared sufficient for our objectives

FIGURE 3 Species-specific responses of tree phenology to climatic variables. Shown is the species-specific correlation coefficient (r) between the phenology score of leafing (first nine species) and flowering (last three species) and different climatic variables. Significances are indicated as follows: *$p < 0.05$, **$p < 0.01$, ***$p < 0.001$. MAT: mean annual temperature; Temp./GDH 1 Jan-date: the mean temperature/ GDH between 1 Jan and the cycling event; Temp./Precip. JFM: January–March temperature/precipitation; OND Temp./Precip. previous: October–December temperature/precipitation of the previous year; GDHyear: mean annual growing-degree hours. The numbers between brackets denote the number of individuals per species

from the mid-1970s onwards, still a period of four decades, and image quality is certainly extremely good since the start of the 21st century. The very good spatial (up to meter scale) and temporal (annual to hourly with CCTV cameras) resolution of repeat video footage can compensate for this weakness. Annually changed camera angles represent a challenge (to relocate the object; Figure 1c) but also an opportunity (to analyse the object from different angles). Although our method appeared to be applicable also to video footage from the 1940s to 1960s (own pretrials, results not shown here), this remains untested. Image enhancement of the older film might solve this issue in certain instances (e.g. via edge enhancement techniques, Vellend et al., 2013). Another important drawback of our method is the potential spatial bias to places where archiving television footage has a long tradition. Still, this is similarly an important drawback of other commonly used methods to assess phenology responses to climate change (see maps in Wolkovich et al., 2012 based on time series and experiments, and Willis et al., 2017 based on herbarium records). Video footage, especially from cycling races, are only available from fixed positions restricted to the route; our technique is inapplicable to study processes in remote areas without cameras.

In sum, we here demonstrate that applying archived video footage to quantify tree phenology responses to global warming is possible with high spatiotemporal resolution and represents an important,

exciting technical advance. The technique can be applied to a wide range of other questions as well, but, as with any other method to study plant phenophases, naturally comes with limitations. Probably the most promising way forward for phenology research is to better integrate all types of phenology data (Willis et al., 2017): observational time series, experimental manipulations of climate, herbarium records, historical surveys of vegetation, historical maps, repeat photographs and other, yet unexploited, sources such as television video footage from broadcast archives. Our research thus calls for further exploitation of video archives in global change biology.

ACKNOWLEDGEMENTS

AUTHORS' CONTRIBUTIONS

P.D.F., P.V. and K.V. conceived the ideas and designed methodology; L.V.L., A.V.D. and C.B. collected the data; L.V.L., C.B. and P.D.F. analysed the data; P.D.F. led the writing of the manuscript. All

authors contributed critically to the drafts and gave final approval for publication.

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