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Phenoclimatology: development and applications in North America

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ABSTRACT

This paper presents a brief overview and history of "phenoclimatology", a subdiscipline of climatology, emphasizing atmosphere-biosphere interactions. Here, we describe the establishment and recent growth in models and forecasts created using *in situ* phenology observations and the factors enabling these advancements, with focus on North America. Most notably, large-scale phenological models paved the way for development of synthetic indices. Such indices can supply an assessment of a location's general phenological response over a standard period, context for comparing regional or local-scale studies, the ability to analyze changes in damage risks for plants, and reconstruction of the timing of events in years past across many regions. As such, synthetic phenological indices have seen wide adoption in estimating spring-season evolution in real time, anticipating short-term impacts of an early or late start to spring, and in assessing changes in the timing of seasonal transitions associated with climate change.

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Phenoclimatology; phenology; models; indices; climate change

Introduction

Phenology is the study of recurring plant and animal life cycle stages, especially their timing and relationships with weather and climate (Schwartz, 2003). The origins of phenological knowledge predate recorded history, stemming from the needs of early societies reliant on environmental understanding for their survival. Cave paintings in Europe dating 15,000 to 40,000 years ago document mating seasons of birds, bison, deer, fish, and horses using a lunar calendar, demonstrating that early humans recognized – and tracked – the cyclic nature of biological events (Bacon et al., 2023). For many centuries, the primary focus of the academic field of phenology was to support improved agricultural practices (Lieth, 1974) and local-scale research centered on establishing relationships between local environmental conditions and plant response.

Phenology changed rather abruptly in the late 1990s with the publication of several influential papers in the journal *Nature*, thrusting phenology into the climate change

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spotlight (Menzel et al., 2000). Late in the decade, Myneni et al. (1997) reported a lengthening of the growing season during the 1980s in mid- to high latitudes based on remotely sensed information concordant with increases in global temperatures and atmospheric carbon dioxide levels. Schwartz (1998) subsequently demonstrated the need to evaluate short-term advancements in spring green-up within the context of changes over longer time periods (multiple decades to centuries) which becomes possible using models based on *in situ* observations of leaf-out and flowering in several cloned plants. Shortly thereafter, Menzel and Fabian (1999) and Crick and Sparks (1999) reported clear advancements in springtime plant and animal activity in Europe using direct observations of organismal activity. The publication of these papers occurred just as satellite-borne sensors made tracking phenology across large areas possible. The advent of the LANDSAT program in the 1970s, which provided regular, repeated observations of the same locations, yielded dramatic visuals of spring plant green-up across the Northern Hemisphere, giving rise to the term "green wave" (Rouse, 1977).

These four papers (Crick & Sparks, 1999; Menzel & Fabian, 1999; Myneni et al., 1997; Schwartz, 1998) collectively made two pivotal contributions to the field. First, using a diversity of approaches, they demonstrated clear advances in springtime activity in plants and animals that could be attributed to increasing temperatures and atmospheric carbon dioxide levels, raising the profile of phenology as a climate change indicator. Second, these works extended the geographic scope of phenological analyses, moving from single sites to broad regions. The impact of these works was outsized, spawning an acceleration of phenological studies facilitating our understanding of changing Earth system interactions from local to global scales. Since the mid-1990s, the number of phenology publications has increased dramatically, from 50 in 1991 to over 500 in 2016 (Chuine & Régnière, 2017; Tang et al., 2016). The value of phenology as a global change indicator was cemented in 2007 when the Intergovernmental Panel on Climate Change acknowledged that phenology "is perhaps the simplest process in which to track changes in the ecology of species in response to climate change" (Intergovernmental Panel on Climate Change (IPCC), 2007).

The sub-discipline of climatology that is focused on establishing relationships between plant and animal seasonal activity and the environmental conditions driving them is recognized as "phenoclimatology." The earliest use of this term can be traced to the 1970s, when Sestoft established the specific weather conditions associated with plant development in Greenland (Sestoft, 1970), though work to match environmental conditions and plant response had been underway for much longer. "Phenoclimatology" received light usage in the agriculture and horticulture realm in subsequent years as researchers characterized the climatological conditions associated with seasonal activity in various species of plants (e.g. Eisensmith et al., 1980; Hickin & Vittum, 1976; E. A. Richardson et al., 1975; Tyson et al., 1975). Until recently, the term largely fell away from the scientific lexicon. The recent and rapid rise in research focused on ecological response to changing atmospheric conditions at larger geographical scales has led to the reappearance of this term at the intersection of ecology, climatology, and global change (Schwartz, 1999, 2013).

The aim of this paper is to chronicle the establishment and growth of the subfield of phenoclimatology, due to its importance as a climate change indicator, with focus on North America. This review is organized around three foci: 1) continental-scale models,

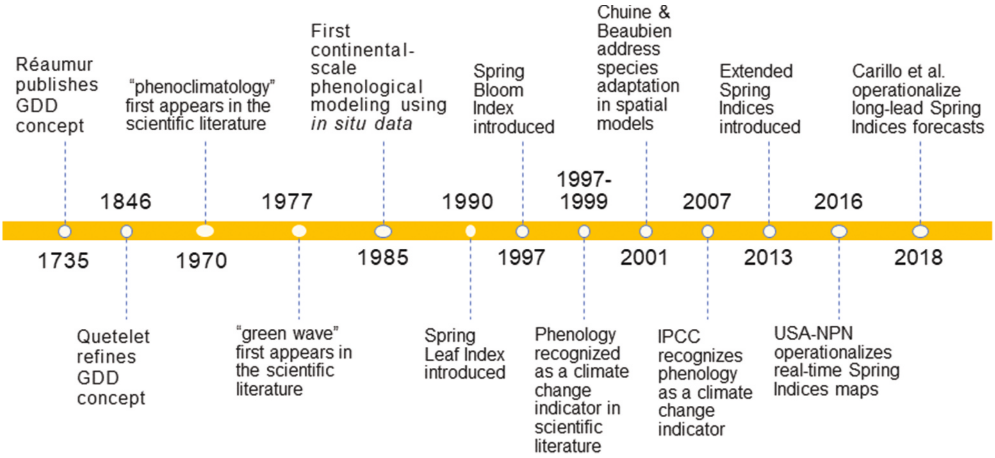

Figure 1. Timeline of major developments in phenoclimatological research.

synthetic indices, and the data necessary for their creation; 2) phenological reconstruction and forecasting: looking backward and forward; and 3) markers of seasonal lower atmospheric and land surface interactions. We provide a timeline of major developments in phenoclimatological research to assist with interpretation (Figure 1).

Continental-scale models, synthetic indices, and the data necessary for their creation

Phenological models spanning local to continental scales

Phenological models, which predict the timing of seasonal biological events based on local environmental conditions, have existed for centuries, extending back to the mid-18th century when French entomologist, René de Réaumur, established that plants must be exposed to a particular amount of warmth to flower. Réaumur's (1735), and that of many of his successors, involved accumulating warmth after a start date, often set at January 1st in the Northern Hemisphere. Thermal units are measured in growing degree days (GDD) – the number of degrees the daily average air temperature exceeds a base temperature, below which the organism remains dormant – or growing degree hours (GDH) – the number of degrees the hourly average temperature exceeds a base temperature. Approximately a century later, Adolphe Quetelet, professor of physics and astronomy at Brussels, Belgium, published his "Law of Flowering Plants," which stated that plants flower after exposure to a specific quantity of heat (Quetelet, 1846). Quetelet's method differed from that of Réaumur's by using degrees of Celsius squared to calculate thermal time, which importantly emphasizes springtime "warm spells" – notably warm conditions that span multiple days and appear to have outsized influence on triggering plant growth.

Because thermal sum models perform quite well at estimating activity in particular organisms where springtime growth is primarily temperature-limited, this approach has been widely implemented in agriculture, horticulture, and pest management applications (Barker & Coop, 2023; F.-M. Chmielewski, 2003; Delahaut, 2003; Schwartz, 1997).

A notable limitation of these models is their difficulty in accounting for nonlinear responses in plants to sustained bouts of warm temperatures, given that thermal sums are linear and thus only indirect measures of plant metabolic processes. Further, phenological model development progress has been almost exclusively related to thermally driven spring phenology, given that environmental factors affecting autumn phenology are seemingly more variable, and therefore not well understood (A. D. Richardson et al., 2013; Yu et al., 2016).

In recent decades, phenological models have become increasingly sophisticated, incorporating additional variables such as winter chill, daylength, moisture conditions, and employing novel predictive techniques. Many phenology models are statistically derived, based on correlations between environmental conditions and plant response (Tang et al., 2016). However, process-based models, which reflect cause–effect relationships between conditions and response, are increasingly being implemented (e.g. Caffarra et al., 2011; Chuine, 2000; Chuine & Régnière, 2017). Mechanistic, process-based models offer the benefit of more realistically reflecting non-linear changes that may arise under novel future conditions, though many of their parameters are still derived from statistical methods. This is why experiments are often necessary to identify the most accurate models (Chuine et al., 2003).

Historically, phenological modeling largely occurred at the site level. A noteworthy recent shift in the phenology world, spurred on by the study of global change impacts, has been the transition from developing models and making predictions at single locations to calculating them across large geographic regions (e.g. continental-scale). Several studies in the 1980s made the first advances in this area, predicting the timing of leaf-out in lilacs across the northeastern USA (Schwartz, 1985; Schwartz & Marotz, 1986, 1988). This work was pivotal in the field of large-scale phenological modeling, demonstrating that models developed using *in situ* observations of plant development in individual species can be used to predict the timing of activity in these species across large regions. The models that emerged exhibited error of six to 7 days, which is similar to the error rate of models constructed at local scales and has proven to be acceptable in a number of applications (Gerst et al., 2020; Schwartz, 1997, 2013; Schwartz et al., 2006). Notably, these models were constructed using observations of leaf and flower development on cloned plants. A major advantage of using phenological observations of genetically identical plants in model construction is that the influence of local adaptation on plant response is eliminated.

The Schwartz and Marotz studies advanced large-scale phenology modeling and a broader understanding of the impacts of global change in two other important ways. First, these studies demonstrated that some of the inherent non-linearities of relationships between air temperature and spring phenological development could be addressed through a more nuanced approach of temperature accumulation than is traditionally achieved in thermal sum models. The refined approach placed greater emphasis on "synoptic events" – high accumulations of warmth associated with specific synoptic weather systems – and "capstone events" – similar high accumulations of warmth associated with synoptic weather systems occurring in a specific sequence during the week preceding the phenological event. By incorporating synoptic events into models, Schwartz and Marotz (1988) demonstrated significantly improved model fits over more simplistic growing degree hour accumulation models as well as the tradeoffs between model complexity and performance. Second, the authors demonstrated that model forms with simple day-of-year phenological dates originating from multiple locations across a large region as the dependent variables in linear regression equations can be constructed to efficiently test the effectiveness of model performance using mean absolute (absolute value of predicted day of year minus observed day of year) and mean bias (predicted day of year minus observed day of year) errors as criteria (Schwartz, 1997; Willmott & Matsuura, 2005; Willmott et al., 2017).

Advancements in computer processing have dramatically increased our ability to make phenological predictions across large regions, and in recent years, many efforts have predicted the timing of seasonal events in plants and animals across the landscape. For example, Jochner et al. (2013) used observations of flowering in birch collected across rural–urban gradients in Germany to establish a predictive model based on accumulated chill, warmth, and daylength cues, underscoring the value of observations collected across geography in predicting plant activity. More recently, Crimmins, Crimmins, et al. (2017) developed simple thermal sum models using observations of leaf-out and flowering collected across the United States and then used these models to predict the timing of activity across the plants' distributions. Prediction error in these models ranged from 6 to 20 days, demonstrating that phenology observations collected on wild plants can yield predictions with accuracy similar to that achieved using cloned plant observations. Prevéy, Parker, Harrington, Lamb, et al (2020, 2020). similarly established growing degree day threshold models for several plant species in the Pacific Northwestern region of the USA using observations collected across a large region and employed these models to predict the timing of plant activity under expected future climate conditions. Likewise, Taylor and White (2020) established a suite of growing degree day models using observations of leaf-out and flowering for dozens of plants collected across the USA and used these models to generate real-time and long-lead forecast maps of plant phenology.

Continental-scale phenological models have experienced several key advancements in recent years. First, it is well-documented that in many wild (not cloned) plants, sensitivity to drivers of phenological events varies across the species' range (Leimu & Fischer, 2008; Liang, 2016; Savolainen et al., 2007). While this fact is widely acknowledged, the variation arising from local adaptation is typically unaddressed in phenology models. However, in a groundbreaking study, Chuine and Beaubien (2001) incorporated differentiated parameter estimates across the range of the species being modeled. Further, Melaas et al. (2013), and more recently, Liang and Wu (2021) and Liang (2023) suggested approaches to account for local adaptation within a species' range. Other work has demonstrated additional improvements that can be garnered with the inclusion of additional data sources. For example, Melaas et al. (2016) combined *in situ* plant phenology observations collected across a region with remotely sensed information to develop and test models of spring leaf emergence.

Generating real-time phenology predictions across large areas

Several efforts use temperature data and other variables to generate real-time predictions of phenological status across space and time that are freely and publicly available. The USA National Phenology Network (USA-NPN) presently generates predictions of

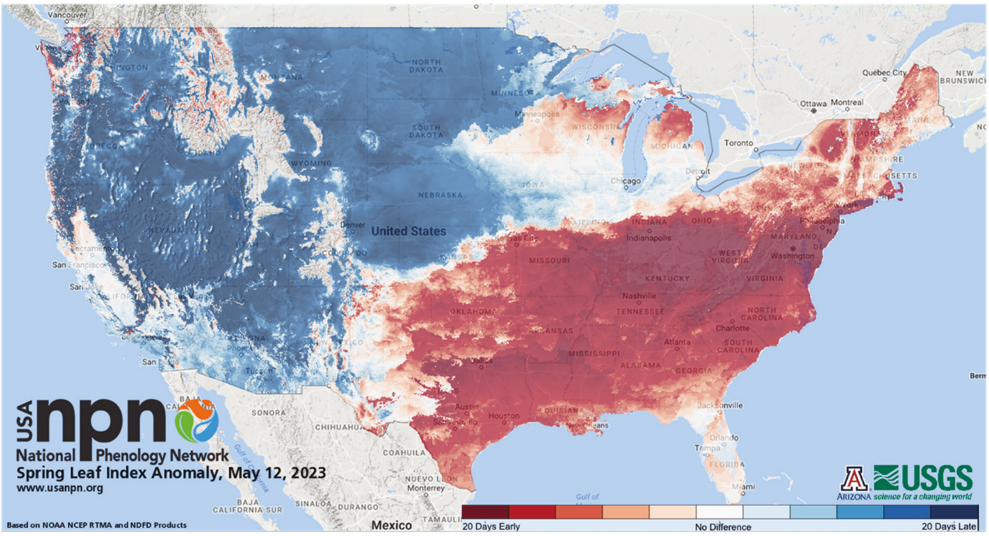

Figure 2. Extended Spring Leaf Index anomaly for the conterminous USA as of May 12, 2023, generated by the USA National Phenology Network (2023). Anomalies are calculated by differencing the day of year the index is reached in the current year to the day of year the index was reached, on average, over the previous three full decades (1991–2020, in this case).

phenological transitions for nearly two dozen invasive plants, pest insects, and agricultural crops across the conterminous USA for the current and upcoming 6 days using thermal sums and other simple phenological models (Barker et al., 2023; Crimmins et al., 2020; Gerst et al., 2021). The Degree-Days, Risk, and Phenological event mapping (DDRP) platform similarly supports the creation of real-time and short-term forecasts of phenological status at the continental scale using thermal time models; several forecast maps are in production at uspest.org (Barker et al., 2020). The Spatial Analytic Framework for Advanced Risk Information Systems (SAFARIS) platform similarly offers predictions of activity in several management-relevant insect pests on a weekly basis (Takeuchi et al., 2023). Finally, the USA-NPN generates real-time maps of the onset of springtime biological activity using gridded temperature data products offered by the U.S. National Weather Service (Figure 2, Crimmins, Marsh, et al., 2017). These maps are widely referenced by the news media to communicate the risk of frost damage to plants, start of the allergy season, the emergence of turf, horticultural, and agricultural pests, and to anticipate the start of flowering in iconic cherry trees.

Moving from continental-scale phenological models to indices

The early work of Schwartz and Marotz demonstrating the ability to develop models using phenology observations collected across a large region paved the way for the development of more synthetic indices. The value of synthetic indices is that these measures indicate the timing of seasonal progression more generally, rather than reflecting biological activity of individual species. As Schwartz et al. (2006) described, rather than reproducing the phenology of individual species, these indices reflect measures of weather conditions that are related to growth and development of many plants. “As such, they provide baseline assessment of each location’s general phenological response over a standard period, supplying a needed context for evaluating and comparing regional or local-scale studies” (Schwartz et al., 2006). Further, as with single species phenological models, such indices can be calculated at any location where the inputs to the indices are tracked. Models driven by widely available data such as daily maximum-minimum temperatures allow for proxy analyses of much larger areas, with greater spatial density and temporal continuity than possible with almost any source of observed phenological data (Schwartz et al., 2006).

In a series of publications in the early 1990s, Schwartz demonstrated that models developed using observations of leaf-out in cloned plants active earliest in the spring season could be averaged to produce an index representing the onset of biological activity among early-season organisms (Schwartz, 1990, 1993, 1997). This model was termed the “Spring Leaf Index.” Using observations of flowering in the same plants, Schwartz created a companion “Spring Bloom Index,” which is reached at a location several weeks after the Leaf Index once additional warmth has accumulated (Schwartz, 1997). Together, these two models comprise the Spring Indices. The Spring Indices have been instrumental in demonstrating advancements in conditions associated with the start of biological activity in the spring (Ault et al., 2015; Izquierdo-Verdiguier et al., 2018; Mehdipoor et al., 2018). Because of their utility in reflecting the timing of springtime activity across large regions, the Spring Indices have been adopted as a climate change indicator by both the U.S. Environmental Protection Agency (Environmental Protection Agency, 2023) and the U.S. Global Change Research Program (U.S. Global Change Research Program, 2024). Recent analyses have confirmed that the Spring Indices accurately reflect the timing of spring activity in a range of plants (Gerst et al., 2020; Schwartz et al., 2013).

An important consideration in establishing phenological indices is to balance their fidelity toward reproducing the growth characteristics of individual species with serving as broader representative indices of multiple species’ responses. For example, earlier forms of the Spring Indices models (Spring Indices “Original,” or SI-o) were designed to incorporate an empirically derived chilling requirement to limit the model’s output to the species’ geographic ranges (Schwartz, 1997). This approach meant that SI-o outputs did not extend to much of the southeastern USA. The current version of the Spring Indices models (“Extended,” or SI-x) eliminates the chilling requirement, with little impact on model accuracy (Schwartz et al., 2013). Using this simpler formulation, the Extended Spring Indices model output extends to subtropical regions and encompasses the entire conterminous U.S.

An additional strength of the Spring Indices models and similar phenological indices (i.e. those that can be calculated from daily maximum-minimum air temperatures) is that they can be combined with other measures to analyze changes in spring frost damage risks for plants. Schwartz (1993) first suggested a simple measure termed the “damage index,” calculated by subtracting the day of year of the latest −2.2°C freeze event from the day of year the Spring Leaf Index was reached. Changes in the timing of these two events are anticipated to affect the chances of freeze damage to sensitive agricultural plants and will likely have implications for species survival in natural ecosystems (Schwartz et al., 2006). The spring of 2012 offered a dramatic demonstration of how an exceptionally early start to the growing season, coupled with a "normal" last frost, can lead to significant horticultural crop damage. These conditions, captured in the Spring Indices, occurred across the north-central and eastern USA, and resulted in $500 M in horticultural crop damage in Michigan alone (Ault et al., 2013).

Phenology observing networks: providing critical ground observations

Calculating the timing of phenological transitions across large regions necessitates observations from many locations within the region to account for variation in conditions and plant response present across space. Historical phenology monitoring networks, established across Europe, China, and a few other countries, mainly to support improved agricultural practices, enabled the first attempts at constructing phenological models intended to make predictions across large regions (Chen, 2013; Menzel, 2013).

Observations originating from these historical observation networks have been instrumental in quantifying phenological change in Europe and China in recent decades (F. -. Chmielewski & Rötzer, 2001; Fu et al., 2014; Ge et al., 2014). As the appreciation of phenology as an indicator of global change has increased, phenology observing networks have been established in the USA, Bhutan, Australia, India, and several other countries (Schwartz, 2013). In many European countries, as well as in Japan and China, these networks are managed by governmental units and observations are regularly collected by paid professionals, ensuring consistently sampled organisms distributed evenly over geography and a low rate of error in species and phenophase identification (Kaspar et al., 2014; Nordt et al., 2021; Renner & Chmielewski, 2022; van Vliet et al., 2003). In other countries including the USA, the UK, Canada, Australia, Bhutan, India, Sweden, the Netherlands, Japan, and Ireland, observations are contributed primarily by volunteers (Schwartz et al., 2013).

Concerns regarding the quality of volunteer-contributed data have been voiced for decades. Volunteer-contributed data can suffer from inconsistent sampling, a bias toward more populated areas, and greater error in species and phenophase identification than professionally collected observations (Crimmins et al., 2022; McDonough MacKenzie et al., 2018). Even with these limitations, networks such as the USA National Phenology Network generate phenology datasets that are of sufficient quality and quantity to be increasingly incorporated into scientific analyses and decision-making, in establishing how phenology is shifting, and – as demonstrated above – in phenology model construction and validation (Crimmins et al., 2022; Feldman et al., 2018; Fuccillo et al., 2014).

Phenology observations contributed by volunteers are also supporting the development of new phenological indices. The authors of this manuscript and others are developing a new suite of "spring development indices" using phenology observations contributed by USA-NPN volunteer observers and U.S. National Ecological Observatory Network (NEON) technicians. These indices are intended to complement and extend the existing Spring Indices models by encompassing more of the growth and development period across the spring season. Observations of activity in several insect pests, invasive grasses, and deciduous trees contributed by USA-NPN volunteers are also supporting current phenology model building and validation activities in several distinct efforts. For example, volunteer-contributed observations of red brome (*Bromus rubens*) and cheatgrass (*B. tectorum*) supported the establishment of flowering and senescence models for these species, operationalized as new short-term forecasts on the USA-NPN website (https://www.usanpn.org/data/maps/forecasts).

Phenological reconstruction and forecasting: looking backward and forward

Reconstructing historical phenology

A major strength of phenological models and indices is that they can be used to estimate when seasonal events occurred at any location or point in time, if model inputs representing the independent variables are available at the appropriate temporal and spatial resolutions. A growing number of studies have used phenological models to reconstruct the timing of past events, though studies that calculate these changes across space are fewer in number. Crimmins and Crimmins (2019) estimated the timing of when various biologically relevant growing degree day thresholds were met across the conterminous U.S. from 1948 to 2016. Their findings demonstrated varying rates of advancement in the timing of various springtime heat accumulation thresholds in the conterminous USA, with the consequence that in some locations, the duration between thresholds being reached is becoming compressed and in others, it is lengthening.

Synthetic indices such as the Spring Indices have also been key in establishing how phenological activity has changed in recent decades, including North America (Ault et al., 2015; Mehdipoor et al., 2018; Schwartz & Reiter, 2000; Schwartz et al., 2013), China (Schwartz & Chen, 2002), Europe (Wu et al., 2016), and most temperate areas of the Northern Hemisphere (Schwartz et al., 2006). A major contribution of these studies is the depiction of varying rates of change across geographic regions. By reconstructing the Spring Indices (SI) across North America each year from 1900 to 2010, Schwartz et al. (2013) showed that springtime activity in the southeastern states appear to come into phase with the rest of the conterminous U.S. during the early 1980s, while a break occurs in the conterminous USA time series, resulting in the timing of spring's onset averaging 3–4 days earlier after that period (Figure 3). Comparison of changes in the southeastern states to the rest of coterminous USA provide important information regarding possible changes in the position and amplitude of the long upper-level wave (ridge in west/trough in east) pattern (Harman, 1991). Further, this SI break appears to align with a "regime change" noted in many other natural phenomena during the 1980s (Reid et al., 2016). Additionally, two recent studies utilized the Spring Indices as a proxy of phenological change to examine the impact of climate change on USA National Parks and Fish and Wildlife Refuges (Monahan et al., 2016; Waller et al., 2018).

When applied to climate model outputs, phenological indices offer an advantage by characterizing projected changes across Earth system models uniformly, as well as providing an independent indicator of climate change influences on ecosystems (X. Li, Ault, et al., 2023). For example, a recent study showed that models of advancement in the onset of the spring season derived from measures of plant growth such as leaf area index (LAI) are weaker than estimates calculated using the Spring Indices (X. Li, Ault, et al., 2023). This finding highlights the magnitude of uncertainty associated with projections of start of spring changes. Reconstructions using phenological indices can also be

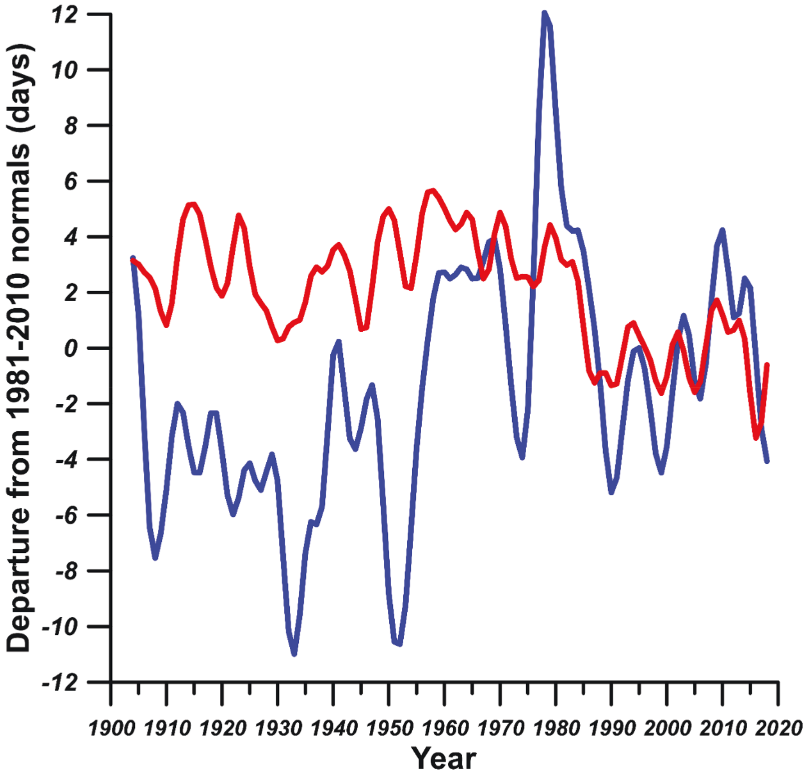

Figure 3. Smoothed (nine-point moving average) extended Spring Leaf Index departures from the 1981–2010 average for the Southeastern USA (blue) and the rest of the lower-48 USA states (red) over 1904–2018 (modified and updated from Figure 2 in Schwartz et al., 2013).

combined with satellite-derived information to fill spatial and temporal gaps, integrating spatial and temporally discontinuous phenological data into a more useful form (Zhao and Schwartz, 2003). When combined in this way, these data provide even more robust estimates of how phenology has changed in recent decades.

Phenological forecasts and projections

Several recent efforts have used the Spring Indices models to predict how the timing of spring might change in future decades and the consequences of such changes. As part of a comprehensive evaluation of change in climate, hydrology, and biophysical indicators in the Northeastern USA, Hayhoe et al. (2007) estimated changes in the start of the spring growing season in recent decades and projected changes in the phenomenon through the end of the century. More recently, Allstadt et al. (2015) predicted an advancement in the start of spring of 23 days by 2100 across the conterminous U.S. under the Representative Concentration Pathway (RCP) 8.5 pathway, with an increased risk of false spring events – early, sustained springtime warmth that prompt biological activity, putting plants at risk to subsequent freeze events – in the Great Plains and Midwest. Labe et al. (2016) similarly evaluated the increased risk of damaging freeze events in the USA following the onset of plant growth under future climate change scenarios. This team's projections estimated conditions like those experienced in 2012 occurring as frequently as once every 3 years by the middle of the 21st century, with clear negative consequences for agriculture. Martinuzzi et al. (2019) likewise estimated increases in false spring risk in future decades with implications for ecosystem services and societal benefits derived from public lands.

Long-term forecasts, predicting the timing of conditions associated with plant and animal activity months, rather than days, into the future have strong value in planning and management applications (Bradford et al., 2018; Dietze et al., 2018). For the most part, phenology forecasts are short term in nature, predicting activity only days into the future (Crimmins et al., 2020; Crimmins, Marsh, et al., 2017; Gerst et al., 2021). However, recent work has enabled long-lead (3-month) forecasts for the Spring Indices. Carrillo et al. (2018) developed an approach to generate long-lead forecasts of daily maximum-minimum air temperatures. These are then used to drive the Spring Indices models to produce the expected timing of spring's onset across the conterminous USA. These products can be issued every 2 weeks from mid-January to the end of March each year and are expected to soon be available operationally (Carrillo et al., 2018).

Markers of seasonal lower atmospheric and land surface interactions

While numerous research efforts have addressed the impacts of weather and climate on seasonal plant growth, a relatively modest number have addressed the reverse. The onset of spring plant growth in temperate climates has direct effects on lower atmospheric characteristics through changes in transpiration, surface roughness, and albedo (A. D. Richardson et al., 2013). However, impacts of these changes are typically obscured in temperature (and other) observations by the variable year-to-year nature of these events, which can differ in timing at many locations by a month or more. Fortunately, using spring phenological events to align multiple locations and year's temperature records into relative "phenological time" makes these impacts of spring plant growth detectable (Schwartz & Karl, 1990). Spring phenology, measured using either direct observations or Spring Indices model output, reveals related seasonal changes in multiple lower atmospheric variables including lapse rate, vapor pressure, visibility, relative humidity, and wind direction (Schwartz, 1992). Subsequent studies examining variations in diurnal temperature ranges across phenological time confirmed the separability of the effects of transpiration from other phenomena like last snow cover and last frost dates. Further, this research confirmed the relationship of phenology to changes in mean ceiling height, mean sky cover, and other variables, as well as defining the "... onset of spring in midlatitudes as a modally abrupt rather than gradual seasonal transition ..." (Durre & Wallace, 2001; Schwartz, 1996).

Additional research has linked the increase in spring lower atmospheric moisture (related to the onset of plant transpiration) to a wide range of phenomena, such as increased instability leading to increased chances of thunderstorm development (Fitzjarrald et al., 2001; Sakai et al., 1997). Further, recent work has demonstrated that spring phenology variations have implications for summer soil moisture availability (Denham et al., 2023). Also, phenological measurements can identify changes in the surface energy balance related to the onset of spring plant growth. With the onset of plant transpiration, the partitioning of net radiation near the surface switches from being dominated by sensible heat to being overwhelmingly latent heat, in moist temperate regions (Schwartz & Crawford, 2001). Finally, it is important to acknowledge that numerous studies of how phenological changes feedback into the atmosphere (facilitated by tower-based measurements in FLUXNET, AmeriFlux, and other similar networks around the world) have greatly enhanced our understanding of atmosphere–biosphere interactions. While even a brief discussion of these contributions is beyond the scope of this review, some selected recent papers are provided here (Beamesderfer et al., 2023; X. Li, T. R. Ault, et al., 2023; Moon et al., 2020; Young et al., 2021, 2022; Ziegler et al., 2023).

Looking forward

Dramatic advancements of computational capacity and the Internet, the availability of remotely sensed data and information, and public engagement and participation in phenology data collection in recent decades have all enabled growth in phenological models and forecasts and their use. Continued – and expanded—*in situ* phenology observation will remain crucial for documenting changes in phenology and in the establishment of new predictive models, forecasts, and indices (Schwartz, 1999).

The development of reliable continental-scale phenological models, driven by widely available simple environmental data, will facilitate the creation of various "seasonal development indices" designed to represent broad aspects of the overall temperate plant community, and tailored to specific research objectives. Such new indices will be used to expand our ability to: 1) understand changes in plant phenology related to climate change since the early 1900s; 2) implement operational systems to issue advanced forecasts and track seasonal plant growth annually in real-time; and 3) project and anticipate changes in plant phenology because of future climate change. Together, these applications will continue to expand the vital contributions of phenoclimatology in global change research and applications.

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Author contributions statement

Schwartz developed the concept and design for the paper and created the initial draft. Both authors took part in all revisions and approving the final version. Both authors agree to be accountable for all aspects of the work.

Data availability statement

This is a review article with no data available except that used to generate Figure 3. These data are available on request.

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