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PERSPECTIVE

Twenty-one questions shaping the future of plant phenology research in the 21st century

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Abstract

1. This Perspective examines the critical frontiers shaping the future of plant phenology research and identifies key emerging challenges and opportunities expected to influence the field in the 21st century.
2. The study is based on a combined approach including a targeted literature review, structured AI-assisted idea generation, and intensive interdisciplinary expert workshop discussions.
3. The resulting research agenda is organized around four principal domains: ecological interactions shaping plant phenology, advanced remote-sensing approaches for monitoring, innovations in phenological modelling and societal implications of phenological change.
4. These domains reveal persistent gaps in current plant phenology research as well as opportunities for significant scientific and practical advances, particularly in integrating ecological, technological and applied perspectives.
5. The synthesis provides practical guidance for future research aimed at improving the understanding, prediction and management of plant phenological shifts, thereby supporting ecological resilience and long-term sustainability.

KEYWORDS
artificial intelligence, ecology, global change, modelling, remote sensing, society, sustainable development goals, tipping points

For affiliations refer to page 11.

1 | INTRODUCTION

Plant phenology, the timing of seasonal biological events in plants, stands at the forefront of ecological research, offering vital insights into the impacts of global change. Understanding spatiotemporal patterns in phenological dynamics is critical to addressing challenges such as adaptation to climate change (Chamberlain & Wolkovich, 2021; Grossman, 2023), biodiversity conservation (McGowan et al., 2021; Morellato et al., 2016), impacts on agriculture (Menzel et al., 2020) and food security (Janni et al., 2024). Despite substantial advances, critical gaps remain in predicting and managing phenological changes across diverse ecosystems (Chuine et al., 2016; Piao et al., 2019; Tang et al., 2016). Existing reviews often focus on specific drivers or regions, while comprehensive frameworks that integrate ecological, technological and societal dimensions remain scarce. Major unresolved issues include the inconsistent integration of reproductive phenology across taxa, limited transferability of models across climate zones, and insufficient use of phenological insights in societal decision-making, ranging from agriculture and health to biodiversity conservation and urban planning. Furthermore, recent methodological developments, such as high-resolution remote sensing, AI-assisted modelling, have yet to be fully synthesized into a coherent research strategy.

To address these gaps and shape future research directions, we identified 21 priority questions for plant phenology research. Our methodology combined a novel AI-assisted ideation process (see Supplementary Materials), a structured literature review, and an interdisciplinary expert discussion. This integrated approach enabled the generation and evaluation of over 600 candidate questions, some from expert insight, others inspired by AI-generated prompts probing phenological challenges through the 21st century. Following a rigorous selection and refinement process, including validation at the FAIR Phenological Modelling Workshop (March 2024, Lorentz Center, Netherlands), we synthesized the most pressing and promising research frontiers.

The result is a curated list of 21 key questions that we believe define the next frontier in plant phenology research (Box 1). These are grouped into four thematic domains: (i) ecology, (ii) remote sensing, (iii) modelling and data and (iv) society; and reflect both persistent knowledge gaps and emerging scientific opportunities (Figure 1; Table S1). In doing so, we extend the tradition of forward-looking agenda-setting efforts such as 'One Hundred Important Questions Facing Plant Science Research' (Armstrong et al., 2023; Grierson et al., 2011).

Authored by a multidisciplinary team of experts, this article synthesizes research priorities that reflect the diversity of plant phenological research globally. By highlighting both persistent and

BOX 1 Deriving the 21 Research Questions

To identify the most pressing frontiers in plant phenology research, we followed a structured and iterative process combining AI-assisted ideation, literature synthesis and expert knowledge (see more details in the SM).

We first employed various large language models (e.g. ChatGPT developed by OpenAI) as brainstorming assistants, prompting them with domain-specific and forward-looking queries. This AI-assisted process generated approximately 600 candidate research questions. The author team then screened these to eliminate redundant, vague, or out-of-scope suggestions, with only about 5%–10% deemed novel or potentially valuable for further discussion. In parallel, we conducted a targeted literature review to survey recent advances and identify gaps across phenological subfields, which informed and contextualized our subsequent expert discussion.

In the next phase, all questions, including those derived from AI, based on literature, and contributed independently by authors, were clustered and thematically coded. This allowed us to identify overlapping concerns, refine wording and ensure representation across major phenological frontiers.

The whole process, including the final selection of questions, took place during the FAIR Phenological Modelling Workshop (March 2024, Lorentz Center, Leiden, the Netherlands) and during multiple follow-up online meetings. In this interdisciplinary setting, participants critically reviewed the longlist, proposed revisions and reached consensus on 21 priority questions. These were grouped into four thematic domains: Ecology, Remote Sensing, Modelling & Data and Society, which structure this Perspective.

The process ensured transparency (all AI-generated questions were catalogued and shared with the author team and workshop participants for open review and critique), inclusivity (the FAIR Phenological Modelling Workshop was designed to engage early career and senior researchers, with attention to gender balance and geographic diversity) and thematic breadth (the initial prompts to the AI were structured to span ecological, technological and societal domains), while also allowing room for speculative or underexplored ideas that may guide future research trajectories. Participants in the FAIR Phenological Modelling Workshop represented institutions primarily based in the Northern Hemisphere but brought expertise and case studies spanning temperate, boreal, Mediterranean and tropical ecosystems. While direct participation from the Southern Hemisphere was lacking, several workshop contributions drew on collaborative work and applications in regions such as East Africa and other tropical systems.

emerging research needs across diverse environmental and socio-political settings, this Perspective aims to guide globally relevant phenological science and support evidence-based adaptation to climate change.

2 | FOUR FRONTIERS FOR THE FUTURE

To steer plant phenology research towards greater ecological and societal relevance, we propose 21 interlinked questions that mark out four key frontiers: Ecology, Remote Sensing, Modelling & Data and Society. Rather than offering a definitive roadmap, these questions are intended to provoke critical reflection and spark future investigations that push the field beyond its current boundaries (Figure 1).

2.1 | Ecology

1. How do interactions between abiotic factors (e.g. temperature, light, precipitation, soil moisture), biotic factors (e.g. pests, pathogens, herbivory, facilitation), global/planetary threats (pollution, invasive species, GHG concentrations) and human management (fertilizer, irrigation, forest management) influence plant phenology? Plant phenological responses are increasingly relevant for addressing environmental challenges and vary across space and time (Morisette et al., 2009). However, beyond temperature and photoperiod, less commonly considered factors also deserve attention (Tang et al., 2016). These include abiotic drivers such as soil moisture (Liu et al., 2022), artificial light at night (Wang et al., 2025) and snow (Slatyer et al., 2022), biotic drivers such as pests, pathogens (Burdon & Bartlett, 2022), herbivory and competition (Ekholm et al., 2020), as well as biodiversity loss (Wolf et al., 2017). However, despite this improved understanding of individual drivers, their *joint* and often non-linear interactions remain insufficiently quantified across ecosystems and temporal scales (Chen & Peñuelas, 2025). Furthermore, drivers of global change, such as air pollutants and elevated CO_2 concentration, human activities and management practices such as fertilizer application and irrigation may also modify phenological responses. Interactions among these jointly determine the timing and plasticity of phenophases, and whether resulting shifts increase fitness or instead elevate ecological risk. Thus, the multitude of these factors and complex interactions—both synergistic and antagonistic—shape the timing of plant phenological events (Piao et al., 2019;

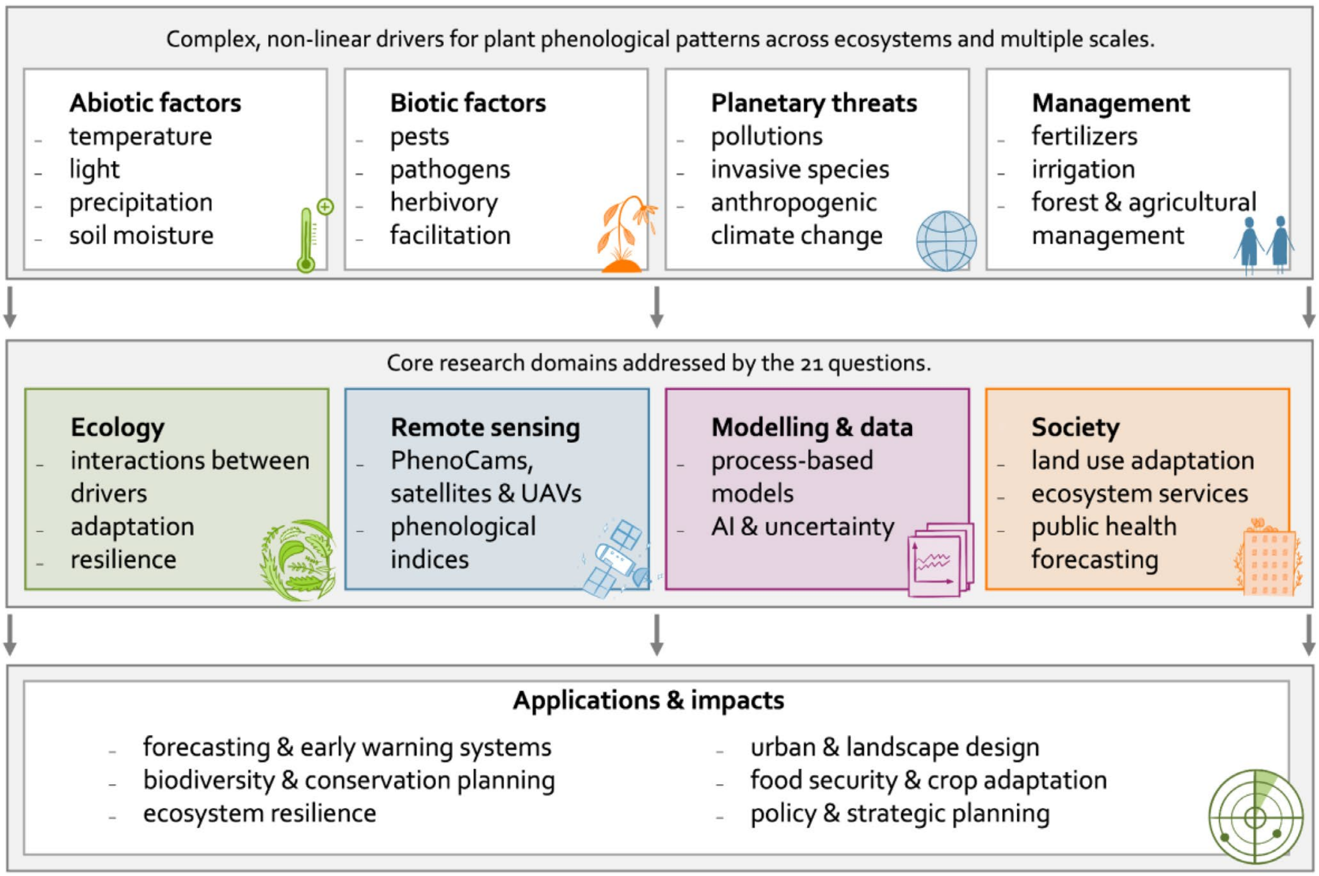

FIGURE 1 Key Scientific Frontiers in Plant Phenology. This figure synthesizes 21 future-shaping research questions in plant phenology, structured across four thematic domains: Ecology, Remote Sensing, Modelling & Data and Society. Each theme includes key challenges and opportunities, accompanied by strategic recommendations for advancing the field.

Zhou et al., 2023). Examples of this complexity are microbes that can impact plant phenology through effects on nutrient acquisition and phytohormone signaling (O'Brien et al., 2021), and the role of biotic interactions within and across trophic levels (de la Torre Cerro & Holloway, 2021). Despite the growing availability of ground- and remote sensing-based data and significant advances in research, mechanistic understanding of the underlying plant phenology responses remains limited (Piao et al., 2019), and cross-scale feedbacks among climate variability, biodiversity loss and land use are rarely analysed in unified frameworks. To improve phenological models, understudied drivers and their interactions should be evaluated for their possible effects across different scales using long-term datasets and, if warranted, integrated into models.

2. How do extreme events and disturbances act as drivers of phenological shifts?

Extreme events like droughts or frosts can significantly affect plant phenology but are less studied than gradual warming effects (Reyer et al., 2013). However, phenological responses to stress are complex, varying by species, provenance and even individual specimens (Menzel et al., 2015), and often cause legacy effects in addition to their immediate impacts (Seidel et al., 2019). More research is needed as extreme events change in timing, frequency, intensity and duration. Additionally, we lack information on less well-studied events, such as hail and thunderstorms. Moreover, compound eco-climatic events (as defined by Bastos et al., 2023) can have synergistic and antagonistic impacts on phenology. Nevertheless, we do not fully understand how response mechanisms may adjust during extended stress periods (Busto & de Yzaguirre, 2024) or how the indirect effects of disturbances such as drought-induced fires and mortality (Allen et al., 2010) drive phenological shifts (precocity or period changes). Phenological monitoring should also be extended to include stress responses in specific plant species, such as late spring frost causing re-sprouting, summer drought leading to premature leaf fall or an autumn rewetting inducing a second flowering phase (García-Mozo et al., 2022). A structured research framework with experimental and data-driven approaches, but also via citizen sciences programmes, is urgently needed to address the complex interactions between extreme events and plant phenology (Chuine et al., 2025). This is important since stress responses can be nonlinear or even bidirectional (e.g. drought could advance or delay flowering), vary with the characteristics of extreme events (i.e. their environmental cues), differ with plant properties (i.e. organismal mechanisms/cues) or their physiological status (being in the acclimatization versus recovery period) and may also comprise longer-lasting effects of multiple extremes (i.e. legacies).

3. What are the drivers of phenological variability within and among plant species populations, including terrestrial and aquatic environments and across taxonomic, temporal and spatial scales, and how can geospatial data help elucidate the interactions between genetic factors, environmental cues, land use changes and phenotypic plasticity?

Plant phenological patterns and responses to climate vary across individual specimens, species, communities, taxa, habitat types, elevation, latitude and growing seasons. Despite extensive research, the factors explaining this diversity of phenological patterns have not been fully understood (Roslin et al., 2021; Wolkovich et al., 2014). Chmura et al. (2019) suggested latitude, elevation, habitat type, trophic level, dispersal strategy, ecological specialization, species' seasonality, thermoregulatory mode and generation time as key drivers for the magnitude and directions of observed trends. However, results are often conflicting. Many authors reported phenological variation between trophic levels (Loughnan et al., 2024), while Roslin et al. (2021) identified a mosaic of changes based on data collected across the former Soviet Union, with the magnitude and direction of shifts varying by trophic level. In the past, macro-phenological research was limited by the lack of large-scale data beyond remotely sensed green-up, restricting investigations into phenology across broad taxonomic and spatial scales (Gallinat et al., 2021). Current new avenues of research, often based on citizen science, focus on predicting and extrapolating plant phenological responses across taxa and spatial scales, using species' functional traits that can be related to phenological variability (Kloos et al., 2024; Rauschkolb et al., 2024).

4. How can phenological research be expanded to better capture reproductive phenology across diverse taxa, including rare and understudied species?

Plant phenological research has historically focused on the main phenological stages that are easily observable, such as flowering and budburst (Vitasse et al., 2022), while greening and browning are the dominant data categories in remote sensing (Morisette et al., 2009). However, reproductive phenology remains underexplored outside the context of agricultural and viticultural systems (Meng et al., 2022). Flowering and fruiting of plants are crucial for ecological niche, abundance and distribution modelling, but basic information is often lacking, especially for orphan species (neglected or understudied species due to their lack of economic or conservation significance or remote habitat locations), as well as for rare and endemic plant species. It is necessary to establish simple and robust protocols for observing maturity stages using agricultural crop expertise to obtain high-quality observations. With increasing abiotic stress during climate change, carryover effects from preceding plant phenological phases may influence subsequent phenological events, even across years (as dormancy or floral induction). Thus, integrating plant phenology of less frequent events as reproductive phenology will require refined modelling approaches, including a broader set of potential drivers. Even so, due to the scarcity of long-term ground observations for many species and events, reliable methods to extrapolate plant phenological responses across taxa, provenances and varieties will be needed.

5. How can we assess adaptation strategies via plasticity versus long-term evolutionary pathways?

Phenological research on natural ecosystems has mostly focused on climate change responses, likely related to short-term plasticity, while largely neglecting phenology's role in ecology and long-term evolutionary pathways (Forrest & Miller-Rushing, 2010; Wolkovich et al., 2014). Recent studies have connected plant phenology to ecological outcomes such as demography (Iler et al., 2021), abundance (Cleland & Wolkovich, 2024), distribution (Chuine, 2010), invasiveness (Wolkovich & Cleland, 2011) and plant performance (Wolkovich et al., 2014) in terms of fitness and survival. Species adaptation to changing environmental conditions involves both phenotypic plasticity and evolutionary pathways. These two are interconnected: for example changes in the genetic composition of populations may result in phenological changes, or plasticity might impede natural selection, and, thus, evolution (Fox et al., 2019). Disentangling plasticity from genetic aspects of phenology remains a challenge, particularly as we may be confronted with adaptive and maladaptive plasticity. The critical question is to what extent plant phenological shifts and their intraspecific variation are the result of plasticity and, if so, whether the degree of plasticity is sufficient for survival while still allowing natural selection and evolution to occur (Price et al., 2003).

6. How can we identify and enhance the resilience of ecosystems at risk from climate-induced changes?

To effectively enhance the resilience of ecosystems at risk from climate-induced changes, it is crucial to develop comprehensive management strategies that account for the complex interactions of abiotic, biotic and human factors. Such strategies should leverage advanced modelling techniques to predict future ecological shifts and identify vulnerable species and communities. This is challenging, since it is impossible to screen all plant species and their interactions. Extrapolating phenological responses across taxa and regions using traits and phylogeny is a necessary step to move forward. Suitable modelling techniques are needed to anticipate future patterns of change. Moreover, plant phenology may be just one factor contributing to maladaptation to novel climate environments, acting through the investment/risk trade-offs of phenological variation, while other factors may also play a dominant role in shaping risk and vulnerability. In agriculture, adjusting sowing times and growing periods, shifting crop cultivars and exploiting phenological diversity can enhance resilience and adaptive capacity (Wolkovich et al., 2017). In forestry, assisted migration, such as planting drought-adapted tree species and provenances, can improve adaptation. However, associated phenological shifts may, in turn, affect biophysical feedback to the climate system and potentially compromise ecosystem resilience, for example the ability to recover after drought (Li et al., 2023).

2.2 | Remote sensing

7. How will advancements in sensors (e.g. multispectral, hyperspectral, SAR, LiDAR) and platforms, including satellite and near-surface remote sensing systems (e.g. UAVs, PhenoCams) enhance the estimation and modelling accuracy of plant phenophases?

Advances in sensors and platforms have greatly improved plant phenology monitoring, enabling high-frequency, large-scale observations. Modern fine-resolution satellites (e.g. Sentinel-2, PlanetScope, Landsat Next) allow monitoring from landscapes (Fox et al., 2019) down to individual fields or trees (Li et al., 2023; Price et al., 2003; Wolkovich et al., 2017). Multispectral time series remain key for detecting phenophases like green-up and senescence, while hyperspectral sensors (e.g. PRISMA, EnMAP) provide detailed biochemical and physiological insights, though their revisit frequency is still low. SAR sensors (e.g. Sentinel-1, NISAR) offer all-weather observations of vegetation structure and moisture, aiding monitoring in cloudy regions and providing complementary information, for example on crop phenology (Satake et al., 2022). UAVs, PhenoCams (Brunner et al., 2019), proximal sensors and crowdsourced imagery (Lehner et al., 2020) provide high-frequency, near-surface data, essential for heterogeneous agricultural (Misson et al., 2011; Wolfe et al., 2016) and forested landscapes (Chuine et al., 2025; Drenovsky et al., 2019; Franklin et al., 2020; Saltelli et al., 2020) and for validating satellite observations. LiDAR enhances these datasets (Hartmann et al., 2022) by capturing 3D canopy structure and phenophases such as budburst and defoliation (Templ, 2025; Vilhar et al., 2018). Integrating ground-based networks with satellite data support hierarchical monitoring, but challenges remain, including scale mismatches (Chambers et al., 2013), mixed-pixel complexity and differences in sensor resolution and revisit times. Data fusion approaches are improving, combining multiple sensors (e.g. LiDAR, hyperspectral, SAR) for more accurate phenology characterization (Schweiger & Laliberté, 2022).

While increasingly sensor options become available that extend capabilities beyond the classical pure multispectral phenology retrieval, revisit times of such options remain often too long for effective description of seasonal vegetation development. Nonetheless, we foresee that, as sensors and platforms develop, a greater variety of high-repeat sensor data will emerge for more precise identification of specific plant phenophases.

Along with that, several other challenges remain. Phenological signals vary across spatial scales (Song et al., 2024) and mixed satellite pixels often integrate multiple species, canopy layers (Yu et al., 2018) and management practices (Bégué et al., 2018), complicating the interpretation of remotely sensed phenophases. Integrating multispectral, hyperspectral, SAR and LiDAR data are methodologically complex due to differences in spatial resolution, revisit frequency and uncertainty structures, while robust data fusion and uncertainty propagation frameworks are still under development (Kahraman & Bacher, 2021). Moreover, remote sensing indicators do not always correspond directly to biologically defined phenophases - particularly for reproductive stages such as flowering - highlighting the need for better harmonization between field observations and sensor-derived metrics (Xu et al., 2024).

Overall, while next-generation sensors and platforms substantially enhance phenophase estimation and modelling accuracy, progress depends on addressing challenges related to scale integration, data fusion, biological interpretation and model generalization. Overcoming these limitations is critical for improving phenological predictions and strengthening assessments of ecosystem responses to climate variability and change.

8. How can the retrieval of phenology information be improved for large areas by effectively linking and integrating ground-based observations with satellite data?

While remote sensors provide an unprecedented synthesis of vegetation dynamics at regional and global scales, significant discrepancies exist between satellite-derived phenological records and biological phases observed in the field, due to differences in spatial scale, spectral coverage and the definition of phenophases. This is further complicated by the fact that precise geographic coordinates of field phenological records are not always known. Addressing this challenge requires improving the representativeness and scalability of field records. Observation networks such as PhenoCams, proximal sensors, UAVs and in situ databases like the National Phenology Network (NPN)60 and the Pan European Phenology database (PEP72564) can capture phenology with fine temporal resolution for specific locations. To effectively combine with satellite-derived information, the network of sites must be representative of the species or ecosystem under study to ensure reliable calibration and validation of satellite phenology retrievals. Integrating in situ with satellite observations allows for a better understanding of how remote sensing signals respond to actual plant phenological transitions.

Studies have demonstrated similarities among plant phenology metrics derived from image time series acquired at different spatial scales, including Sentinel-2 and MODIS satellites, UAV acquisitions and PhenoCam (Chuine & Régnière, 2017) records. These comparisons primarily reflect changes in vegetation greenness and may not directly align with specific vegetation phenophases or productivity. Although different data sources generally agree in tracking vegetation greenness, satellite and near-surface phenology measurements often diverge in late spring and autumn (Pearson & Dawson, 2003; Templ et al., 2017). Furthermore, because multiple plant species are often contained within a single satellite pixel, remote sensing typically provides a measure of Land Surface Phenology (LSP), which may not directly correspond to in situ observations of key plant phenophases (Harris et al., 2014). Differences in viewing geometry can further affect measurements, leading to dissimilar greenness responses between oblique-viewing PhenoCams and near-nadir satellite observations (Watson-Parris et al., 2022). Similarly, estimates of the start and end of photosynthetic activity from FLUXNET carbon flux data may differ from LSP metrics depending on the forest ecosystem considered (Rasp et al., 2024).

Besides independent comparison of phenology observations, harmonization or calibration of in situ and satellite-derived measures may help in improved phenological estimates. Calibrating satellite phenology extraction algorithms using ground observations improves the biological interpretability of remote sensing metrics and allows phenological models to be adjusted for different vegetation types. Capturing the dynamics of mixed and evergreen forests, as well as forest understory vegetation, remains challenging because it is difficult to disentangle overlapping phenological signals from multiple species60 and detect subtle changes in evergreen species (Christin et al., 2019).

The literature emphasizes the value of combining multiple observation platforms to cover scales from individual plots to entire regions (Moon et al., 2021; Thapa et al., 2021). Time-series analyses that integrate satellite observations with near-surface sensors provide a more robust basis for detecting phenological events and help overcome spatial resolution limitations inherent in traditional satellite imagery. Sensor fusion approaches, including the integration of optical, radar or high-resolution satellite data such as PlanetScope, offer additional avenues to reduce uncertainty in estimating phenological transitions, though methodological integration remains complex. Deep-learning-based approaches have shown to be effective tools for integrating multiple satellite sensor series with field data (Lobert, 2023). Developing phenology products that explicitly incorporate field records and observations from phenological networks is critical for advancing the field (Studer et al., 2007). Using ground observations as 'anchors' to calibrate and interpret satellite-derived phenology enables more accurate extrapolation of phenological dynamics to larger scales, enhancing confidence in monitoring ecosystem responses to environmental change.

9. How can remote sensing techniques be utilized to detect and monitor climate-driven extreme events and stress factors, like droughts and heatwaves, that impact plant phenological cycles across diverse ecosystems?

Remote sensing technology can monitor variations and anomalies in crop growth (Paul & Pandey, 2014; Schneider et al., 2024) and forest health (Zhang et al., 2024) in consequence to heatwaves and droughts, over large areas. Spatial and temporal resolution represents the most significant constraint on the performance of remote sensing data. For instance, Sentinel-2 data (10-m resolution) can detect early leaf shedding that is often missed by moderate-resolution (500 m) MODIS imagery, thereby enabling the tracking of the forest's responses to drought at the canopy level (Katal et al., 2022). However, current remote sensing systems are still limited in detecting these changes in small forest patches, which are observable only within a short window of a few weeks (Katal et al., 2022). Further advances in sensor technology are expected to allow finer-scale detection of such changes.

In addition, the deployment of phenocams is also one promising direction for improvement. Compared to satellite data, phenocams offer higher spatial and temporal resolution, which is more efficient in monitoring different ecosystems, including mountain grasslands (Morales-Castilla et al., 2020), forests (Caubel et al., 2015) and agricultural fields (Memmott et al., 2007). However, existing phenocam networks are constrained by their limited spatial coverage, typically restricted to small, instrumented plots. As a result, they are currently more suited for monitoring relatively homogeneous regions. Future developments may expand the observational range of individual cameras or enable coordinated multi-camera systems to cover broader regions.

Another emerging trend involves the use of multi-source data to enhance the explanatory power of analytical models. For instance, combining thermal time into Sentinel-2 time series can reduce the variability in vegetation index profiles across years and locations. By creating typical stress-free temporal profiles for crops, anomalies from such profiles can be detected in-season at the sub-field level (Sgubin et al., 2018). Such integration of meteorological and multispectral data could serve as an initial step towards more robust monitoring frameworks for weather impacts on crops and other vegetation.

2.3 | Modelling and Data

10. How do we add more biological meaning to our physiological, process-based models?

Improving the accuracy and applicability of plant phenological models requires a holistic integration of phenology with plant ecophysiology and individual-level carbon, nutrient and water cycles. This integration should be built on a strong knowledge base of the molecular and genetic mechanisms that underlie phenological responses at the individual-plant level (Satake et al., 2022). These allow researchers to map how genes and molecular pathways interact to express phenological patterns in response to internal and external cues. For example, a drought characterized by multiple interacting cues such as low soil water potentials, high vapour pressure deficit and low leaf water potentials can elicit different responses at different times: a spring drought may inhibit budburst (Misson et al., 2011) while a summer drought may elicit premature leaf fall (Wolfe et al., 2016). However, the effects of such environmental stresses are often poorly represented in phenological models (Grossman, 2023). In turn, detailed phenological models are imperative to modelling carbon and nutrient dynamics, as exemplified by the importance of root and leaf development in resource acquisition and competition, and nutrient remobilization mechanisms during leaf colouring (Drenovsky et al., 2019). Overall, the challenge lies in building multi-scale models that incorporate a broad range of interacting physiological and phenological mechanisms. However, the inclusion of such new processes generally involves additional parameters, often poorly constrained by observations. Model refinement may thus be done at the expense of robustness and the predictive power of models (Franklin et al., 2020). Adding complexity should be done carefully, ensuring that parameter uncertainty is quantified and that this uncertainty is propagated when making projections - a necessary step to ensure that projections remain useful to decision-makers (Saltelli et al., 2020).

11. How do we find the right balance between theoretical concepts, various data sources, and robust inference methods to reduce the uncertainty of phenological models?

Uncertainty in plant phenological modelling arises from various sources, and it impacts the accuracy and reliability of simulations. Modelling dynamic systems have inherent limits of predictability, stemming from the complexity of natural processes that may not be fully understood, or from limitations in data quality. Model-based uncertainties occur due to simplifications or assumptions made within models and are often exacerbated by data scarcity or poor data quality. Model weighting (Brunner et al., 2019) or quantifying uncertainty sources (Lehner et al., 2020) of climate models are approaches that can be used to improve the understanding of associated uncertainties when dealing with multi-model ensembles and their applicability could be investigated for the use of uncertainty estimates in phenological models, to quantify uncertainties in phenological data and different model components. Furthermore, methodologies that incorporate both model and data uncertainties are crucial. Martínez-Ferrer et al (Hartmann et al., 2022). demonstrated this using neural networks for biophysical parameter estimation with uncertainty quantification. Using data from multiple phenology monitoring networks and datasets, whenever available, can also help to quantify data uncertainty (Vilhar et al., 2018). Another relevant aspect around data uncertainty stems from the scarcity of observational data or missing quality protocols, especially in understudied regions or systems. Challenges in data collection and availability (Templ, 2025) can lead to data gaps and inaccuracies (Chambers et al., 2013) that affect the accuracy and reliability of model outputs. Implementing rigorous quality protocols for data collection and estimating uncertainties during modelling are hence essential steps to improve the reliability of plant phenological models. Proper quantification of uncertainty is especially crucial when working to support stakeholders in making informed decisions about the changing landscape of plant phenology under climate change (van der Bles et al., 2019).

12. How important is the feedback between changing plant phenology and other components of the Earth system?

Plant phenology is expected to change in response to rapidly shifting climate conditions, which may trigger feedback in Earth system dynamics, because vegetation plays a pivotal role in the carbon cycle, the water cycle and the energy balance. Changes in the timing of budburst and leaf colouring will change the timing and duration of photosynthesis and transpiration, the cascading effects of which are hard to predict given the complexity of the Earth system dynamics they interact with. A longer growing season logically results in increased carbon assimilation through photosynthesis, but whether this also leads to increased ecosystem productivity and subsequent carbon sequestration is not evident (Körner et al., 2023). Leaf transpiration drives the movement of water vapour into the atmosphere, cooling the surface directly through the dissipation of thermal energy in the form of latent heat and indirectly through the formation of clouds that raise the Earth's albedo. As such, vegetation not only impacts local microclimatic conditions but is a key driver of the global climate, which in turn impacts plant phenology. Understanding the interactions between plant phenology and other components of the Earth system is critical for predicting, mitigating and adapting to climate change impacts (Piao et al., 2019; Richardson et al., 2013; Satake et al., 2024).

13. How can plant phenological models be adapted to ensure their transferability and reliability across climates and taxa?

Historically, plant phenological models are often descriptive and have often been calibrated on a limited set of observational data, for specific plant species and spatiotemporal conditions (Chuine & Régnière, 2017). The limited model transferability that results from such narrow calibration conditions is a crucial hurdle to the use of phenology models to predict phenology under future conditions, and to the integration of such models into large-scale Earth system frameworks. The use of synthetic datasets (artificially generated datasets that mimic real-world data but are created using models, simulations or algorithms rather than direct observations) to simulate potential future climates could be beneficial to evaluate transferability across climates (Templ et al., 2017). Similarly, using bioclimatic envelopes (Pearson & Dawson, 2003), or extending data inputs to include a broader range of climate scenarios (Harris et al., 2014) that plants have not historically experienced but might face in the future could be useful to evaluate transferability. Process-based approaches that are calibrated to a broad range of inputs may be used to improve transferability across different combinations of taxa and climates if they can be based on robust insights into the eco-physiological drivers of plant phenology across taxa. Similarly, research into non-terrestrial plants, such as aquatic and wetland species, could enrich understanding of broader ecological dynamics to further improve model transferability. Research on marginal, emergent and floating-leaved aquatic plants remains underrepresented compared to extensive studies on deciduous woodlands, highlighting a gap in our understanding of aquatic plant responses to phenological shifts driven by climate change. Where large datasets exist, machine learning techniques may be used to improve process-based models by detecting evidence of patterns and interactions that may not be evident otherwise. The sensitivity of these models to changes in climatic conditions of the magnitude that is expected over the 21st century should also be evaluated to raise confidence in future projections. Finally, model validity and transferability may be improved by establishing clear benchmarking frameworks to validate phenological models in a range of ecosystems and climatic settings, including conditions beyond those of the species' current distribution range. Such endeavours have been proven useful in other disciplines, for example, Weather & Climate (Rasp et al., 2024; Watson-Parris et al., 2022).

14. How can AI improve data processing and phenological modelling?

AI and machine learning offer the promise of enhancing the accuracy and scalability of plant phenology modelling, offering novel ways to analyse and interpret complex ecological data (Christin et al., 2019). These technologies excel in extracting potentially meaningful patterns from a vast array of data sources, including satellite imagery, ground observations and unstructured data, thereby enriching our understanding of phenological patterns (Czernecki et al., 2018; Katal et al., 2022). Therefore, by adopting sophisticated AI-based data assimilation methods, the creation of high-quality plant phenology datasets and big data processing workflows can be improved. Machine Learning and traditional process-based (PB) methodologies can also be combined through hybrid modelling, which synergistically combines the strengths of both approaches, AI's scalability and generalizability, with the detailed, ecological insight of PB models (Zhang et al., 2024). This integration can not only improve computational efficiency but also enhance the models' applicability across diverse ecological scenarios due to improved generalization. Further AI advancements include foundation models that employ innovative training techniques by masking data points during the training process, which the model then must learn to fill (e.g. masked token learning). This encapsulates transferred learning, which improves generalization capabilities and can thereby improve extrapolation predictions, for example, for future climates with unprecedented climate characteristics or understudied geographic regions (Schneider et al., 2024).

2.4 | Society

15. How can we utilize phenological data to adapt agricultural and forestry practices to the changing phenological cycles of major crops and tree species due to climate change?

Climate change affects agricultural and forest ecosystems, altering key stages of both reproductive and vegetative processes such as germination, budburst, flowering and fruiting. These changes, especially those related to rainfall and temperature, can alter fertilization and fruit ripening, reducing yields and threatening food security. On the other hand, the increase of CO_2 can enhance fruit ripening and even fruit production (Paul & Pandey, 2014). Warmer late-winter temperatures can advance flowering and budburst in perennials, increasing their exposure to late frosts (Chamberlain & Wolkovich, 2021; Sgubin et al., 2018). Extremely dry springs can lead to lower pollination, which due to climate change, can be even compensated by autumn flowering and winter fruiting (García-Mozo et al., 2022). All this can disrupt the traditional alignment between crop growth and environmental conditions, such as appropriate temperature and water availability, making crops more vulnerable; including changes in pest–pollinator interactions add further challenges (Caubel et al., 2015; Memmott et al., 2007; Morales-Castilla et al., 2020). Phenological data at the species level are essential for understanding how crops and trees respond to temperature extremes and water stress. This information can be incorporated into models to predict shifts in growth cycles, helping to adjust planting, irrigation and harvesting practices (Le Roux et al., 2024). Phenological data can also support the selection of agronomic species and varieties better suited to regions under environmental changes (Burgos-Miranda et al., 2025).

16. How will changes in the phenology of allergenic plants affect the incidence and severity of allergic and respiratory diseases in humans?

Climate change is significantly affecting the phenology of allergenic plants such as ragweed (*Ambrosia artemisiifolia* L.), birch (*Betula*

BRITISH ECOLOGICAL SOCIETY Functional Ecology

pendula L.) and grasses, which may display advanced flowering and extended growing seasons (López-Orozco et al., 2023). Such shifts lead to heightened pollen production, contributing to longer and more severe allergy seasons. Such changes exacerbate allergic and respiratory conditions in the human population, including hay fever and asthma, impacting public health (Menzel et al., 2020; Ziska et al., 2019). Rising temperatures and increased CO_2 levels further stimulate pollen production and prolong flowering periods; thereby, the introduction of alien plants into new regions exposes the population to 'new' allergens in the area, increasing allergy rates (Ziska, 2016). The urban environment complicates this issue further by affecting pollen distribution, necessitating the use of advanced modelling techniques to accurately forecast pollen and allergen levels. Technological advances in pollen monitoring allow for real-time data collection, which can be integrated with public health systems to develop early warning systems and provide personalized medical advice, thus improving the management of allergy seasons (Maya-Manzano et al., 2023). Such objectives, however, can only be reached through multidisciplinary research aiming to enhance predictive models and develop effective strategies to mitigate the human health impacts of phenological changes.

17. How will changes in plant phenological cycles affect plant–pollinator interactions, and what implications will this have for agricultural production and biodiversity?

Climate-induced shifts in the phenological cycles of plants, such as changes in flowering times, significantly impact plant–pollinator interactions (Kehrberger & Holzschuh, 2019; Rafferty & Ives, 2011), leading to mismatches where pollinators such as bees may not find necessary resources when they emerge from hibernation (Memmott et al., 2007). Such mismatches can reduce food availability for pollinators, potentially diminishing their populations and disrupting the quantity and quality of pollination service, which are crucial for many crops and wild plants. The resulting decline in pollination can lower fruit and seed production and quality, threatening food security and biodiversity (Potts et al., 2016; Trunschke et al., 2024). To address these challenges, an integrated approach involving enhanced monitoring of both the plants and the pollinators, predictive modelling of phenological events, and adaptive management strategies is essential. Conservation efforts and habitat restoration can support pollinator populations by providing diverse flowering plants throughout the season. Additionally, implementing pollinator-friendly agricultural practices, such as reducing pesticide use and planting cover crops that benefit pollinators, can mitigate the adverse effects of these phenological changes (Wei et al., 2021).

18. What phenological insights will be needed to design and manage urban green spaces that provide ecosystem services, improve public health and enhance urban resilience to climate change?

Urban green spaces enhance ecosystem services, public health and urban resilience to climate change. Effective design and management of these areas require comprehensive phenological insights to optimize the timing of biological events such as flowering, fruit ripening or leaf fall. Green spaces in cities mitigate urban heat island effects, purify air and support biodiversity, especially when they are composed of plant species that offer year-round benefits. For instance, plants with staggered flowering and fruiting periods maintain aesthetic and ecological functions across different seasons (Lafortezza et al., 2013). Urban areas, with their unique microclimates, can feature plant phenology that differs markedly from that of rural surroundings, complicating the management of urban flora (Jochner & Menzel, 2015). Urban planners should employ advanced monitoring and make use of phenological data in landscape design to select plant species that are adapted to local climates but that do not exacerbate allergy risks without provoking allergy problems (Hernández-Ceballos et al., 2024) and are capable of withstanding future climatic shifts. Additionally, understanding plant phenology can minimize the impacts of allergenic plants, since the garden management can be more effective. It may also enable enhancing thermal comfort by optimizing shade and cooling benefits of urban green spaces (Moreno et al., 2024). Phenology research can thus contribute to ensuring that urban green spaces remain beneficial amid changing climatic conditions.

19. How can understanding phenological patterns enhance predictive models for the emergence and spread of pests and diseases?

Climate change is impacting the emergence and spread (which may expand to new geographical areas) of pests and diseases in agriculture and forestry, which threatens food security and plant health. Phenological data help to predict pest activities and disease outbreaks, enhancing management strategies. For instance, warmer temperatures may accelerate pest life cycles (e.g. bark beetle outbreak in Norway spruce forests), increasing infestation frequency and severity (de Groot & Ogris, 2022), while changes in precipitation patterns may favour fungal and bacterial diseases (Delmas et al., 2024). Accurate phenological models can forecast such outbreaks by integrating plant phenology, as the timing of pest emergence and pathogen infection often coincides with specific plant phenophases. Understanding these interactions informs timely interventions such as pesticide applications and biological control, thereby enabling optimized pest management with reduced environmental impacts. Additionally, phenological insights allow raising of the resistance of crops to pests and diseases by supporting the development and selection of provenances and varieties whose susceptible phenological stages fall outside periods of high pathogen pressure. Changes in plant phenology can also influence animal and human health; extended growing seasons can increase the activity periods of disease vectors such as mosquitoes and ticks, heightening the risk of vector-borne diseases such as malaria and Lyme disease (Altizer et al., 2013).

20. How can advancements in plant phenology research be strategically aligned to support the achievement of specific Sustainable Development Goals (SDGs)?

Advancements in plant phenology research are crucial for supporting various Sustainable Development Goals (SDGs)—these targets and indicators that UN member states are expected to use to frame their agendas and political policies. This research directly contributes to Food Security (SDG 2) by temporally focusing early warning and index insurance mechanisms on assessing anomalous vegetation productivity (Vrieling et al., 2016) and optimizing agricultural practices such as planting and harvesting times to adapt to shifting climate conditions, potentially reducing crop losses. In terms of Health and Well-being (SDG 3), phenological monitoring of allergenic plants and disease vectors can forecast health risks related to allergies and vector-borne diseases, which climate change might exacerbate (Altizer et al., 2013). For Sustainable Cities and Communities (SDG 11), applying phenological data in urban planning enhances green spaces that improve air quality and reduce urban heat, contributing to sustainable urban environments (Cariñanos et al., 2019). Climate Action (SDG 13) benefits from phenology research by enhancing predictive models that forecast ecological responses to changing climate conditions (European Commission. Joint Research Centre, 2020). This insight allows for better preparation and implementation of adaptation strategies (Rojo et al., 2021). Lastly, Life on Land (SDG 15) is supported as phenological insights inform the timing of conservation and land management practices, crucial for maintaining biodiversity and ecosystem health. By aligning phenological research with these SDGs, it is possible to forge strategies that not only

BOX 2 From Questions to Action—A Phenology Research Action Checklist

The 21 key questions proposed in this Perspective spotlight critical gaps and emerging priorities in phenological science. Here, we translate these challenges into a forward-oriented action checklist tailored to researchers, funders and decision-makers. Rather than passive reflection, each point emphasizes practical steps to catalyse future-ready phenology research.

Researchers: Expand Scope, Methods and Integration

- Incorporate multiple interacting drivers by designing experiments or models that combine abiotic, biotic and anthropogenic factors (e.g. drought × pathogens × land-use).
- Prioritize neglected phenophases and taxa (e.g. reproductive events, senescence, non-temperate species), particularly in regions like the tropics and Southern Hemisphere where data are sparse.
- Integrate phenological data with plant traits, genetics and ecosystem functions to advance understanding of plasticity vs. adaptation.
- Link field observations with remote sensing and modelling frameworks to capture phenology across scales, from local to global.
- Leverage AI and hybrid modelling to uncover hidden patterns, but embed these approaches in biologically meaningful frameworks and assess their transparency and reproducibility.

Applied Scientists and Practitioners: Translate Insights into Practice

- Use phenological trends to inform climate-resilient land management, such as adjusting sowing dates, tree planting schedules or urban green infrastructure.
- Model species interactions (e.g. pollinators, pests, pathogens) using phenological mismatches as early warning indicators.
- Develop forecast systems for agricultural risks, frost damage, allergy alerts or phenology-based biodiversity indicators.

Data Stewards & Infrastructure Developers: Build Fit-for-Future Systems

- Ensure phenology data collection includes diverse species, phenophases, and underrepresented biomes.
- Enable interoperability by linking ground-based data (e.g. phenocams, sensors) with high-resolution remote sensing and open-model platforms.
- Uphold FAIR principles, metadata standards and uncertainty metrics to enable reusability, reproducibility and long-term value.

Funders & Policymakers: Align Investment with Emerging Needs

- Design calls that prioritize data integration and cross-scale phenological modelling, especially for climate extremes and ecological tipping points.
- Support longitudinal monitoring in biodiversity hotspots, urban regions and agricultural systems—where phenology is both vulnerable and actionable.
- Fund interdisciplinary hubs where ecologists, data scientists, health researchers and urban planners can co-design phenology-informed solutions.

enhance ecological resilience but also promote sustainable human communities.

21. How can integrated phenological research guide our strategies to enhance ecosystem resilience and human well-being?

Integrated phenological research (the combination of multiple disciplines, data sources and methodological approaches) may contribute to enhancing our ability to anticipate and respond to potential tipping points. Tipping points arising in ecosystems because of the crossing of environmental thresholds (Dakos et al., 2019) and their cascading effects leading to forest dieback and pollination system collapse. These phenomena often occur when ecosystems face compounded stresses, such as repeated droughts or concurrent disease pressures, which push them beyond thresholds of resilience (Moore, 2018; Senf et al., 2020). Tipping points can lead to abrupt, sometimes irreversible shifts with cascading impacts on biodiversity and human well-being.

Early warning signals (EWS, Scheffer et al., 2009) are indicators that can help detect the onset of critical transitions in ecosystems before they occur. By harnessing advanced AI and predictive models that incorporate diverse data sources, we may become able to detect EWS of tipping points (Jiang et al., 2018). Although early warning signals have traditionally focused on external factors like climate stress (Scheffer et al., 2009), observations of trees adapting to stress before forest decline (Bussotti & Pollastrini, 2021) highlight the need for future research to consider how external and internal factors together affect an ecosystem's resilience. For instance, ecosystems with a variety of species with high adaptive capacity (an internal factor) may better withstand or recover more quickly from severe weather events (an external factor) compared to ecosystems with less diversity (Bussotti et al., 2015).

Legacy effects, where past disturbances influence future ecosystem responses, complicate tipping point predictions (Cuddington, 2011). For instance, historical droughts can predispose forests to higher mortality under subsequent stress events, creating feedback loops that amplify vulnerabilities (Senf et al., 2020) or even delay mortality (Seidel et al., 2019). Recognizing these effects is crucial for designing adaptive strategies that mitigate long-term impacts. Phenological insights can also inform proactive management, such as adjusting agricultural practices (Le Roux et al., 2024; Morales-Castilla et al., 2020) to sustain food security and employing targeted conservation efforts to strengthen ecosystem resilience. As the frequency of extreme weather events increases throughout the 21st century (Lange et al., 2020), research needs to provide insights (onset and progression of tipping points) that can help predict and prepare for the cascading effects on ecosystems and human societies. By aligning predictive models with adaptive management practices, we can better safeguard ecological and societal well-being.

3 | CONCLUDING REMARKS AND FUTURE OUTLOOK

Our review underscores a pressing need to rethink and expand the methodologies used in plant phenology research to better anticipate and mitigate the ecological and societal impacts of climate change. The 21 questions we have identified serve as a catalyst for advancing our understanding of plant phenological processes and their broader implications across ecological and societal dimensions.

Significantly, this paper challenges the traditional scopes of phenological studies by highlighting the necessity of integrating advanced technological tools like AI and high-resolution remote sensing (Questions 7–10). These tools are not just enhancements but necessities for capturing the complex dynamics of phenology across various scales and contexts. Such integration promises to reveal subtler, yet crucial, ecological interactions and tipping points (Questions 1–6) that conventional methods might miss.

Equally important is the need for more robust and transferable phenological models that incorporate biological realism, integrate diverse data sources and improve predictive accuracy across taxa and climatic gradients (Questions 11–15). Addressing these modelling challenges is critical for ensuring that phenological research can effectively inform both ecological forecasting and practical applications.

Moreover, our study highlights a critical gap in how phenological data aligns with societal needs. By directly connecting phenological research with the Sustainable Development Goals, we propose a framework where phenology is not just a field of academic inquiry but a foundational element in strategic planning for food security, biodiversity conservation and urban development (Questions 16–21). This approach demands a shift from viewing phenology merely as a biological observation to recognizing it as a tool for policymaking and societal advancement (Box 2).

AUTHOR CONTRIBUTIONS

Mahdi Khodadadzadeh, Annette Menzel, Raul Zurita Milla, and Inaki García de Cortázar-Atauri conceived the ideas and designed the methodology. Mahdi Khodadadzadeh and Raul Zurita Milla developed the AI methodology. Barbara Templ, Annette Menzel, Sebastian Lehner, José A. Oteros, Ester Prat and Victor Van der Meersch led the writing of the original manuscript draft. Barbara Templ, Annette Menzel, Johanna Kauffert, Eike Lüdeling, Emma Izquierdo-Verdiguier, Anton Vrieling, Sebastian Lehner, Jorad de Vries, Ursa Vilhar, Gal Oblišar, José A. Oteros, Duan Keke, Inaki García de Cortázar-Atauri, Victor Van der Meersch, Haiyin Ye, Mahdi Khodadadzadeh and Francois Rebaudo contributed critically to manuscript revisions and editing. Annette Menzel developed the visualization concepts. Mahdi Khodadadzadeh and Annette Menzel co-supervised the study. Johanna Kauffert and Barbara Templ coordinated project administration. All authors contributed critically to the drafts and gave final approval for publication.

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CONFLICT OF INTEREST STATEMENT

The authors have nothing to report.

DATA AVAILABILITY STATEMENT

No new empirical data were generated or analysed in this study. The manuscript is based on published literature and expert discussion. AI-assisted ideation outputs used during the question-generation process are described in the Supplementary Materials.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

Figure S1. Twenty-one challenges and opportunities in plant phenology research by the 21st century. This figure lists the 21 most important research questions in plant phenology categorized into four thematic areas: Ecology, Remote Sensing, Modelling & Data, and Society. Each category represents a crucial aspect of phenological research, from fundamental ecological processes to technological advancements, data integration, and societal applications. These questions provide a research roadmap to enhance monitoring, modelling, and applied solutions for global environmental challenges.

Table S1. Overview of plant phenological research priorities: challenges, opportunities, and recommendations.

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