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Research Article

Data integration advances reproductive phenology research across temporal, spatial and taxonomic scales

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Climate change is altering plant reproductive phenology; however, a scarcity of long-term, systematic monitoring hinders our ability to quantify and predict these responses in many parts of the world. We addressed this gap by demonstrating how data integration can be used to produce a synthesised record of reproductive phenology observations (flowering and fruiting) that spans longer time periods, larger spatial scales, and includes more species than any single source alone. Using Australian subtropical rainforest trees as a case study, we integrated reproductive phenology observations from both common data sources – published datasets, herbarium specimens, and citizen science records – and previously untapped expert botanical knowledge, including private photographic collections, field notes, and seed collections. Data integration yielded 110 657 records of flowers or fruits from 915 species (representing half of all subtropical rainforest tree species) spanning 255 years (1770–2025). We found that different data sources provided unique information across temporal, spatial and taxonomic dimensions. Herbarium specimens provided the longest taxonomic coverage, while citizen science contributed the most recent observations. Critically, 197 species (21.5%) were represented from only a single source, including 154 species represented solely by herbarium specimens and 46 species in expert botanist collections. While 46.6% of species had fewer than 50 observations, for many species, these represent the only available historical phenology data. This integrated dataset may be the only available resource for establishing pre-industrial baselines for the reproductive phenology

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of Australian subtropical rainforest trees. This would not have been possible without the engagement and contributions of the local botanical community, which greatly expanded the research capacity beyond conventional data sources.

Keywords: baselines, biodiversity data, climate change, flowering and fruiting, herbarium, long-term botanical monitoring

Introduction

Across the globe, shifts in the timing of biological events are becoming some of the most visible and measurable indicators of climate change (Primack et al. 2009). In temperate systems, advancing phenophases are disrupting plant–animal interactions that have sustained ecosystems for millennia (Butt et al. 2015, Rafferty et al. 2015). Some spring-flowering plants now bloom before their specialist pollinators emerge (Burkle et al. 2013, Kudo and Ida 2013), while fruiting times increasingly mismatch with the migration patterns of seed-dispersing birds (González-Varo et al. 2021). These disruptions to pollination and seed dispersal have the potential to trigger cascading effects on reproductive success, population dynamics, and broader ecosystem processes, including carbon sequestration (Penuelas et al. 2009, Butt et al. 2015, Scheffers et al. 2016).

Of particular importance are cycles of flowering and fruiting, collectively referred to as plant reproductive phenology, which underpin food webs and ecosystem function (Scheffers et al. 2016, Tang et al. 2016, Pearse et al. 2020). Yet, research connecting phenology with climate change primarily comes from areas with pronounced seasons, such as the temperate Northern Hemisphere, where extreme seasonality makes phenological shifts more noticeable (Davis et al. 2022a). Significant gaps remain in the scientific understanding of both baseline phenology patterns and the impacts of climate change in the Southern Hemisphere and some tropical and subtropical systems (Mendoza et al. 2017). This knowledge gap is particularly significant, given that two-thirds of tropical tree species globally rely on vertebrate seed dispersal (Osuri et al. 2016, Bush et al. 2020, Fricke et al. 2025), suggesting potential for many, as yet unknown, cascading ecological consequences triggered by shifts in plant phenology.

Long-term phenological monitoring programs remain scarce in the tropics and subtropics, which limits our understanding of baseline phenological patterns and climate-driven changes. Historical work on tropical phenology has been limited to a few sites with permanent infrastructure, leaving significant gaps in global phenology networks and datasets (Chambers et al. 2013, 2017, Hacket-Pain et al. 2022, Wright et al. 2022, Primack et al. 2023). To address these data gaps, researchers are increasingly turning to novel data sources, including herbarium specimens, citizen science observations, remote sensing, and expert knowledge (Primack et al. 2004, Tang et al. 2016, Gallinat et al. 2018, Ellwood et al. 2019, Ouédraogo et al. 2020, Miller et al. 2021, Garcia-Rojas et al. 2022, Park et al. 2023b, Yoder et al. 2024). However, individual data sources have inherent limitations: herbarium specimens can exhibit significant collection bias (Daru et al. 2018), citizen science observations are often temporally and spatially clustered (Tiago et al. 2017), and there may be many unrecognised sources of data that are unpublished and inaccessible. To overcome these individual limitations, data integration – combining phenology observations from multiple sources – has emerged as a valuable approach, with particular relevance for data-scarce tropical and subtropical regions (Tang et al. 2016, Chambers et al. 2017, Mendoza et al. 2017).

The Australian subtropical rainforests exemplify the challenges of understudied phenological systems. These forests harbour exceptional biodiversity (> 1800 tree and shrub species) and endemism (> 180 flora species) (Crisp et al. 2001, Williams et al. 2011, Weber et al. 2014), and are included in the UNESCO-listed Gondwana Rainforests of Australia (World Heritage Committee 2025). However, Australian subtropical rainforests remain among the least represented in the global phenology literature (Chambers et al. 2013, 2017, Wright et al. 2022). The region experiences seasonal climatic patterns and supra-annual climate variations (i.e. associated with the El Niño–Southern Oscillation, or ENSO), which may make it sensitive to climate change (Cai et al. 2023). Albeit sparse, published research on the phenology of these forests suggests variable reproductive patterns ranging from reliably annual to supra-annually sporadic flowering and fruiting events (Innis 1989, Mo and Waterhouse 2015, Williams 2021). There are also anecdotal reports of masting behaviour (Hickey and Wilkinson 1999, Williams 2021, Wright et al. 2022). Thus, at the very least, phenological patterns and cues in Australian subtropical rainforests appear to be complex.

Here, we explore phenological research opportunities in an apparently data-sparse region by evaluating how integrating multiple sources expands data coverage compared to a single source alone. We are not starting from scratch, Australia has a long history of botanical collecting, which provides substantial herbarium records that have already demonstrated their value for phenological research in the region (Boulter et al. 2011). The area's accessibility and global biodiversity significance also attract professional botanists and citizen scientists. However, no single data source is likely to provide comprehensive coverage across the temporal, spatial and taxonomic scales needed to fully understand the range of baseline phenologies or recent climate change-driven shifts in these diverse forests. We set out to fill spatial, temporal and taxonomic gaps to produce longer-term and more complete phenological records for the region.

Our work was guided by the idea that different phenological data sources provide complementary, rather than redundant, observations of plant reproductive phenology.

We define complementary sources as those that fill gaps in temporal, spatial and taxonomic coverage, or that increase sample sizes beyond what any single source could contribute. Specifically, we hypothesised that: 1) herbarium specimens offer the greatest temporal depth, 2) citizen science provides the broadest contemporary (e.g. the last 25 years) spatial coverage, 3) sampling effort exhibits phylogenetic structure, with certain lineages being over-represented due to traits that make species more conspicuous or accessible to observers, and 4) that data integration increases research capacity through both expanded coverage (temporal, spatial, and taxonomic) and increased observation density per species, compared to any single source contribution. To test these hypotheses, we compiled, standardised, and integrated phenological observations from six data sources: published studies, herbarium specimens, citizen science observations, expert botanist photographic collections, field notes, and seed collection records. Collation, standardisation, and integration enabled us to quantify the complementarity among data sources and evaluate phenological research opportunities emerging from the synthesised dataset.

Material and methods

Study system and species selection

We used the National Vegetation Information System (NVIS) Major Vegetation Groups to define the current distribution of rainforest vegetation (Australian Government 2020). We then filtered this area to subtropical rainforests, which are generally small, semi-fragmented patches characterised by closed canopies (> 70% cover) in the eastern coastal and semi-coastal ranges of Queensland and New South Wales (Webb 1959, 1968). Along with the core humid subtropical rainforests usually occurring in coastal higher rainfall areas (> 1300 mm) and higher fertility soils (Complex Notophyll Vine Forest to Notophyll Vine Forest) we include seasonally dry subtropical rainforests commonly referred to as dry rainforests (Araucarian Notophyll, Microphyll Vine Forests) and simpler structured subtropical rainforests growing on lower fertility soils commonly referred to as Warm Temperate Rainforests (Simple Notophyll Vine Forest and Simple Notophyll Microphyll Vine Forest). We also included subtropical montane rainforests occurring in cooler, cloudier mountain ranges at higher altitudes > 900 m, locally called cool temperate rainforests (Microphyll mossy fern forests) (Webb 1959, 1968, Floyd 2008). We include the usually lower canopied drought-adapted vine thickets and brigalow bottle tree softwood scrubs from western low rainfall areas (semi-evergreen vine thickets and brigalow *Acacia harpophylla* open forests; Keith et al. 2004, Neldner et al. 2014) (Fig. 1). We compiled a comprehensive species list of all trees and shrubs occurring in our study flora from two authoritative floristic sources: Tropical rainforest plants (Zich et al. 2020) and Rainforest plants of Australia: Rockhampton to Victoria (Harden et al. 2024). We excluded subspecies and variants to reduce taxonomic complexity and standardised all names using the Australian plant census (APC) alignment package 'APCalign' in R (Wenk et al. 2024, www.r-project.org). Our final species list represented 1813 species.

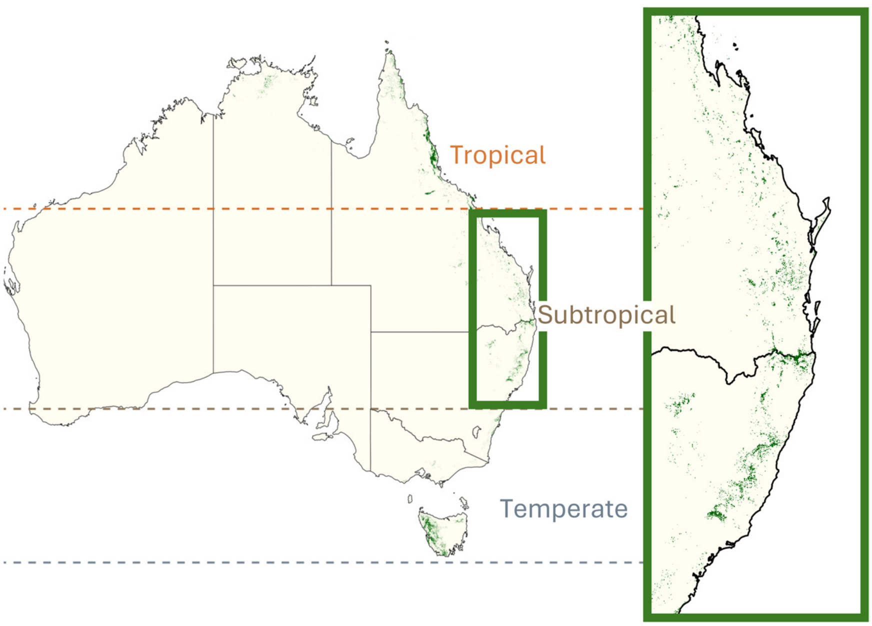

Figure 1. Distribution of current Australian rainforests across rainforest climate zones. The map displays the current distribution of subtropical rainforest areas (green) using the National Vegetation Information System categories of 'Cool temperate rainforest' and 'Tropical or subtropical forest' (Australian Government 2020). Broad geographic zones are indicated by dotted lines, delineating tropical, subtropical, and temperate zones. The green inset indicates the subtropical study region (21–35°S, 150–155°E).

Data collection – published datasets

We located published phenology data according to the guidelines of the Preferred reporting items for systematic reviews and meta-analysis (PRISMA; Page et al. 2021) and utilised the web-based platform Covidence for processing (Covidence 2024). To be eligible, studies must be located within or adjacent to a subtropical rainforest and include flowering and/or fruiting observations on trees or shrubs for periods of more than one year. The initial searches yielded 174 (Scopus) and 163 (Web of Science) studies, with an additional 21 studies identified through other database searches such as Google Scholar. After removing duplicates and further screening, 101 unique studies were identified as eligible. When relevant studies were identified, we approached the authors to determine whether they would be willing to share their raw data (Mo and Waterhouse 2015). Where this was not possible, we extracted data from tables or figures (Innis 1989).

Data collection – herbarium specimens

Herbarium specimens are a major source of historical phenology data; many specimens are collected during reproductive periods and include detailed annotations on flowering and fruiting (Park et al. 2024). This is particularly true for Australia, where herbarium collections provide extensive temporal coverage (Daru et al. 2018). We extracted occurrence data for our target species from the Global Biodiversity Information Facility (GBIF) using the 'rgbif' package (Chamberlain et al. 2025). To select records that provide phenological observations, we identified specimens containing reproductive material based on annotations made in the 'reproductiveCondition' field. Using regular expressions, we identified annotations containing variants of 'flower', 'bud', 'fruit', or 'seed'. Observations explicitly indicating absence (e.g. observations containing 'not', 'no', or similar negation terms) represented < 2% of records.

Data collection – iNaturalist citizen science

iNaturalist is an increasingly important resource for global observations of species occurrences from citizen scientists. Data aggregators, such as GBIF, regularly incorporate verified iNaturalist observations; however, these represent only a subset of all records (Mesaglio 2024). Therefore, we extracted observations directly from iNaturalist to provide a more comprehensive coverage using their API and web interface. We first obtained iNaturalist Taxon IDs for each species from our species list using custom R functions from the 'httr' (Wickham 2023) and 'jsonlite' (Oom 2014) packages. We constructed URL-based searches for three categories: flowering and fruiting observations (records specifically annotated). We spatially constrained searches to the subtropics of Australia and included both 'research-grade' and 'needs ID' classifications to maximise data coverage while maintaining reasonable taxonomic reliability.

Data collection – botanist photograph collections, fieldnotes and seed collections

Expert botanists often collect photographic observations in the field, with many focusing on reproductive events and specific species (Fig. 2). We obtained both historical slide collections and modern digital photography with detailed metadata from multiple botanists. For collections of digital photos, we included all photo records where a species and location were recorded and extracted date and time metadata from the photos. We developed a machine learning pipeline using the Roboflow platform with the vision transformer (ViT) architecture (Dwyer et al. 2025) to categorise photos into three groups: flowers, fruit, or no reproductive material. The model was trained on 4143 manually annotated images and achieved an accuracy of 93.1% in identifying flowers and fruits. When location information was not available in photo metadata, we either manually determined location information or used the 'tidygeocoder' package (Cambon et al. 2021) to obtain the latitudes and longitudes associated with photo locations. Many ecologists and botanists also maintain extensive unpublished field notes. These observations frequently span multiple years and provide detailed phenological information from specific locations. We contacted rainforest ecologists and botanists to identify unpublished field notes, observations from PhD theses, and ongoing research projects within our study area. Botanists working for native plant nurseries and private collectors maintain detailed records of seed collection dates and locations for restoration and commercial purposes. These records provide a unique means of obtaining presence data on when species were fruiting, with high spatial and temporal precision. We contacted native nurseries and private collectors within our study area to access historical seed collection records.

Data standardisation

The information from each data source was standardised using data quality extraction processes from Park et al. (2024) and in line with the Darwin Core in R (Wieczorek et al. 2012).

Phenological variable calculations

The final dataset contained two variables representing reproductive conditions: flowering and fruiting. Observations were coded as 1 (present), 0 (confirmed absent), or NA (not applicable, e.g. an observation of only flowers would have an NA for fruit).

Temporal cleaning

All observations were standardised to the unique month and year they were observed in – the finest temporal scale shared across all data sources, although for many sources, we do have precise collection dates. Observations with exact dates were aggregated to the month-year level, while those lacking month-level precision or containing implausible dates were excluded from the analysis.

Spatial cleaning

Since spatial precision varied across sources – from exact GPS coordinates in citizen science observations to locality descriptions, such as a suburb location in expert photos – we documented the spatial uncertainty for each observation as a radius in kilometres. We excluded observations with obviously erroneous coordinates (e.g. points falling in the ocean or outside

Figure 2. Examples of diversity of flowers and fruits from expert photos of Australian subtropical trees and shrubs from different taxonomic groups. Flowers: (top row) basal angiosperms *Eupomatia bennettii* (Eupomatiaceae), *Endiandra floydii* (Lauraceae), *Daphnandra tenuipes* (*basaltica* ms) (Atherospermataceae). (Second row) Monocots *Cordyline congesta* (Dracanaceae), *Archontophoenix cunninghamiana* (Arecaceae), *Linospadix monostachyus* (Areacaceae). (Third row) Eudicots *Akania bidwillii* (Akaniaceae), *Capparis arborea* (Capparaceae), *Eucryphia jinksii* (Cunoniaceae). (Bottom row) Other Eudicots *Gmelina leichhardtii* (Lamiaceae), *Barklya syringifolia* (Fabaceae), and *Brachychiton discolor* (Sterculiaceae). Fruits: (top image) *Endiandra floydii, Cryptocarya laevigata, Vitex lignum vitae, Macadamia tetraphylla, Davidsonia jerseyana, Elaeocarpus grandis, Archontophoenix cunninghamiana, Davidsonia johnsonii, Macaranga tenarius, Sloanea woollsii, Gossia fragrantissima, Cryptocarya rigida.* (Middle image) *Commersonia bartramia, Flindersia bennettiana, Mischocarpus pyriformis, Syzygium hodgkinsoniae, Parsonsia straminea, Hibbertia scandens, Araucaria cunninghamii, Calamus muelleri, Acronychia imperforata, Podocarpus elatus, Ficus watkinsiana, Synoum glandulosum, Cupaniopsis newmanii, Mucuna gigantea*. (Bottom image) *Endiandra lowiana (virens), Toona ciliata, Freycinetia scandens, Mischarytera lauteriana, Ficus coronata, Ficus henneana, Ficus watkinsiana, Hedraianthera porphyropetala, Elattostachys bidwillii, Archontophoenix cunninghamiana, Cupaniopsis parvifolia, Elaeagnus triflora, Cryptocarya macdonaldii, Beilschmiedia elliptica, Guioa acutiflora* and *Elaeocarpus grandis* (Kin Kin Creek, QLD; Dec 2014). Photos: L. Weber.

Australia) but retained those with larger spatial uncertainty to preserve historical records. This uncertainty measure is included as a variable in our synthesis to quantify location precision.

Taxonomic cleaning

All species names were standardised to their currently accepted nomenclature using the 'APCalign' package (Wenk et al. 2024), which resolves synonyms and outdated names. For consistency across data sources, we aggregated all identifications to the species level, excluding subspecies and variety designations. Observations identified only to genus or family level, or with ambiguous identifications, were excluded.

Complementarity analysis

To quantify the extent that different phenological data sources provide complementary rather than redundant observations, we evaluated our four hypotheses.

We assessed temporal coverage by examining the distribution of observations across three time periods: historical records (1770s–1970), mid-historical (1971–2000) and contemporary (2001–2025). For each period, we calculated: 1) total flowering and fruiting observations, 2) percentage of observations contributed by each source, and 3) sources providing exclusive temporal coverage. We examined the seasonal distribution of flowering and fruiting observations within each time period by grouping observations by months to assess the consistency of phenological observations through time.

We characterised the spatial distribution of phenological observations relative to the mapped rainforest extent using the 'terra' R package (Hijmans 2026). Using the three temporal periods outlined above, we mapped all observations to identify spatial patterns in historical and contemporary time periods. To assess ecological relevance, we created 10 km buffers around subtropical rainforest areas using the National

Table 1. Summary of flowering and fruiting observations from sources used in the phenology data synthesis. Each source is broken up into the total observations and the number of species it contributed. The number of data contributors, e.g. for the herbarium records, refers to the number of unique herbaria that contributed specimens to GBIF, meeting the data download criteria. Additionally, five botanists contributed photo collections, etc. *Published studies have few fruiting observations relative to total observations, due to these sources having time series presence/absence observations, something that is not available for most other sources. Additionally, no published studies reported flowering observations.

Data source	n observations	n species	n contributors	Year range	Flowering observations	Fruiting observations
Published studies	8799	101	2	1979–1992	NA	844*
Herbarium specimens	52 564	839	19	1770–2025	26 818	25 746
iNaturalist records	26 023	528	1	1980–2025	13 833	12 190
Botanist photo collections	9017	693	5	1966–2025	5059	4051
Botanist field notes	9637	418	2	1965–2009	3234	5248
Seed collections	4617	385	3	2000–2024	NA	4617

Vegetation Information System categories of Cool temperate rainforest and Tropical or subtropical forest (Australian Government 2020) (accounting for spatial uncertainty in coordinates and habitat boundaries) and calculated the proportion of observations falling within these buffers across all three temporal periods.

We evaluated the taxonomic representation by visualising the phylogenetic coverage at the family level using the 'V.PhyloMaker2' package (Jin and Qian 2025) and the number of flowering and fruiting observations in the synthesis for each family. For each data source, we calculated the total number of species contributed, the number of species unique to each data source, and the number of species shared between source combinations to identify which sources contributed to the occurrence of rarely observed versus commonly observed species. This approach allowed us to assess the degree to which data sources complement each other by contributing unique observations and species versus providing additional coverage for the same species across the phylogenetic tree. To test whether sampling effort was phylogenetically biased, we assessed phylogenetic signal in observation counts per species for all 915 species. We calculated Blomberg's K (Blomberg et al. 2003) and Pagel's λ (Pagel 1999) using the 'phytools' R package (Revell 2012) with significance for K assessed using 999 permutations. Observation counts were log-transformed to meet the assumption of normality. These metrics are used to test if closely related species have a more similar number of observations than expected when compared to a model of no structure.

To evaluate whether integration creates new phenological research capacity, we quantified the proportional increase in total observations when all sources were combined compared to the largest single source (herbarium specimens). We also assessed the final observation counts for each species in the synthesis by grouping species by observation frequency (< 50, 50–150, 150–500, 500–1000 and > 1000 observations) to evaluate the number of species that are data-sparse (< 50 observations) versus data-sufficient (> 100 observations).

Results

The integration of six phenological data sources yielded 110 657 reproductive observations, representing 915 species, with observations spanning the years 1770–2025. We found that different sources provided unique observations across temporal, spatial and taxonomic scales for Australian subtropical rainforest phenology (Table 1).

Temporal coverage

As predicted, herbarium specimens provided continuous temporal coverage spanning the entire 255-year study period and offered exclusive (except for three historical photos) coverage of historical observations (1770–1970: 20 444 observations; Fig. 3a). No other source captured data before 1966, making herbarium specimens irreplaceable for reconstructing baseline phenological patterns. While herbarium specimens maintained continuous coverage over time, their proportional contribution declined from 100% between 1770 and 1970 to 56% between 1971 and 2000 and 20% between 2001 and 2025, despite an increase in absolute numbers. This demonstrates that relying solely on herbarium data would miss most contemporary observations (Fig. 3). Phenological activity occurred throughout the year across all periods. Flowering observations peaked from September to November, and fruiting observations from December to April across all time periods (Fig. 3).

Spatial distribution

We found that both citizen science observations from iNaturalist and herbarium specimens provided the broadest spatial coverage in the contemporary period 2001–2025 (Fig. 4). These two sources captured observations across the full extent of the study region, whereas published studies were restricted to two specific sites and expert collections (field notes, photos, etc.) were concentrated near the collector's home location and well-visited rainforest sites (Fig. 4c). All sources had high ecological relevance, with more than 90% of observations consistently occurring within 10 km of mapped

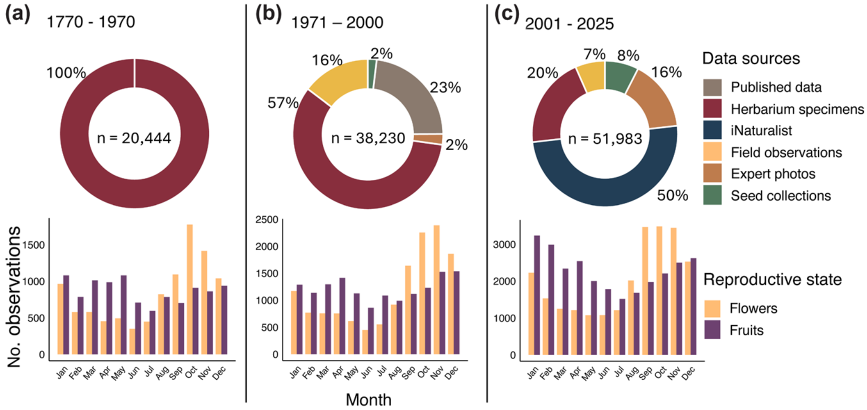

Figure 3. Temporal coverage of phenological observations. All panels show the proportion of observations contributed per data source (top) and the monthly distribution of flowering and fruiting observations (bottom) across three temporal periods: (a) historical 1770–1970, (b) mid-historical, and (c) contemporary. Sample sizes are indicated in the centre of the doughnut chart numbers outside show the % of observations contributed by different sources.

rainforest boundaries across time periods (1770–1970: 92%; 1971–2000: 96%; 2001–2025: 94%).

Taxonomic representation

The integrated dataset represented 50% of the rainforest trees and shrubs in our original species list and 81 of 102 rainforest plant families, though observation intensity varied markedly, with only 27 families exceeding 1000 observations (Fig. 5a). Contrary to our expectation of phylogenetic bias in data availability, we found no evidence of phylogenetic signal in observation counts per species (Blomberg's $K = 0.025$, $p = 0.25$; Pagel's $\lambda < 0.062$, $p = 0.2649$; $n = 915$ species). Indicating that, for the species in the synthesis, sampling effort was distributed across the phylogeny rather than concentrated in particular lineages.

Expert collections contributed unique taxonomic coverage as predicted, with 46 species found exclusively in these non-traditional sources across the full synthesis. The photo collections contributed 31 unique species, while seed collections and field observations provided six and two unique species, respectively. Combined with the 154 unique species from herbarium specimens, this demonstrates clear taxonomic complementarity. When assessed by time period, expert photographic collections contributed 59 unique species during the mid-historic period (Fig. 5b) and therefore captured diversity that would have otherwise been missed for this specific period.

Increased observation density

The full dataset produced using multi-source integration had substantially better spatial, temporal, and taxonomic coverage. The combined dataset of 110 657 observations represents a 111% increase over herbarium specimens alone (52 564 observations), the largest individual data source. More dramatically, the contemporary period (2001–2025) contained 51 983 observations – a 154% increase over the historical period (1770–2000), largely due to citizen science and expert sources. Despite these gains, 46.6% of species had < 50 observations, with approximately 70% of underrepresented species having had both flowering and fruiting observations (Fig. 6).

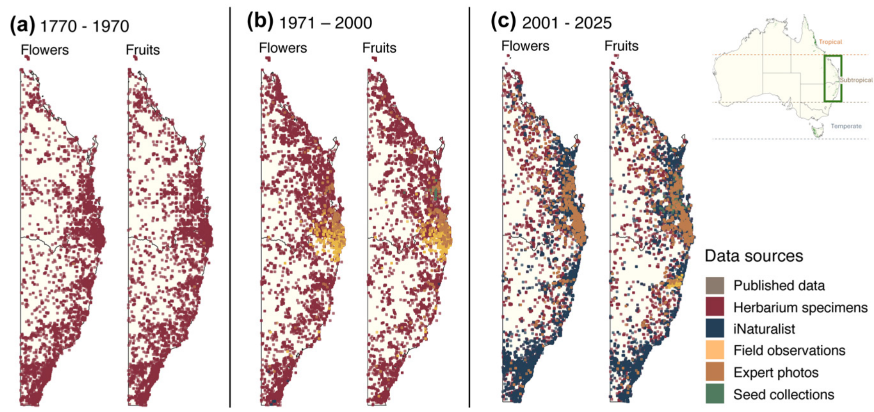

Figure 4. Spatial distribution of reproductive phenology observations from various sources. Maps show Australian subtropical rainforest flora flowering and fruiting observations for three time periods: (a) 1770–1970, (b) 1971–2000 and (c) 2001–2025. The mapped region spans from 21 to 35°S and 150 to 155°E.

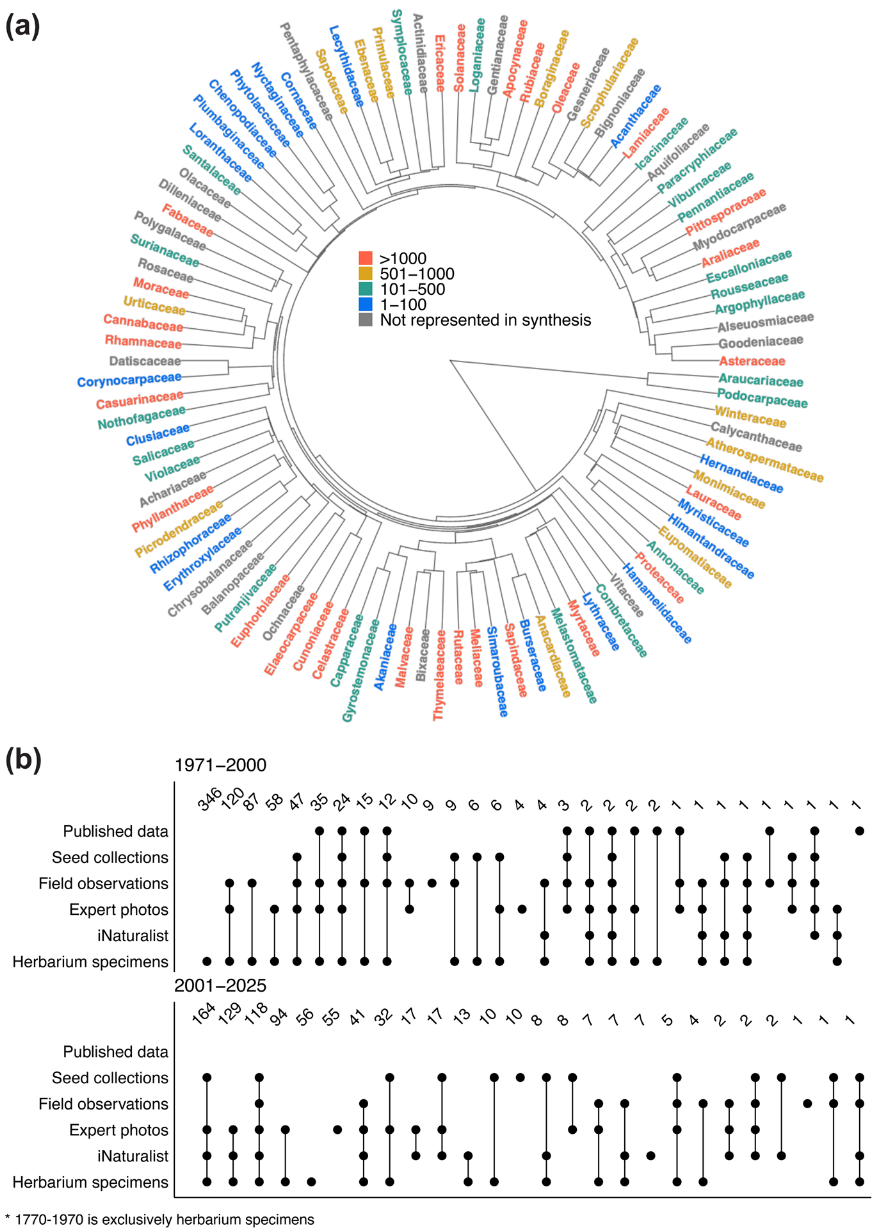

Figure 5. Taxonomic coverage of flowering and fruiting observations. (a) Phylogenetic tree showing the total families (102) represented in our Subtropical Rainforest tree species list. Grey names indicate families not represented in the synthesis (n = 21); a total of 81 families were represented in our synthesis, encompassing 915 species. We note that families with many genera and species may also have more observations due to this diversity. (b) The number of species represented in different combinations of sources from 1971–2000 (top), and 2001–2025 (bottom), numbers above bars indicate total species counts per unique source combinations. We do not show 1770–1970 as this was represented by herbarium specimens alone; there are 657 species represented in this time period.

Discussion

This synthesis demonstrates that different data sources are complementary rather than redundant in terms of temporal and taxonomic coverage, at least for Australian subtropical rainforest trees. The synthesised dataset contained 110 657 observations from 915 species across 255 years, with no single source capturing more than half of this information. This complementarity was particularly evident in both the taxonomic representation from expert botanists' unpublished photo collections (31 unique species) and the distinct temporal patterns. Herbarium specimens dominated historical records, while expert botanists made significant contributions in the mid-historical and contemporary periods, and citizen science contributed substantially between 2000 and 2025.

A synthesis dataset produced through data integration would likely enhance phenological research capacity, especially

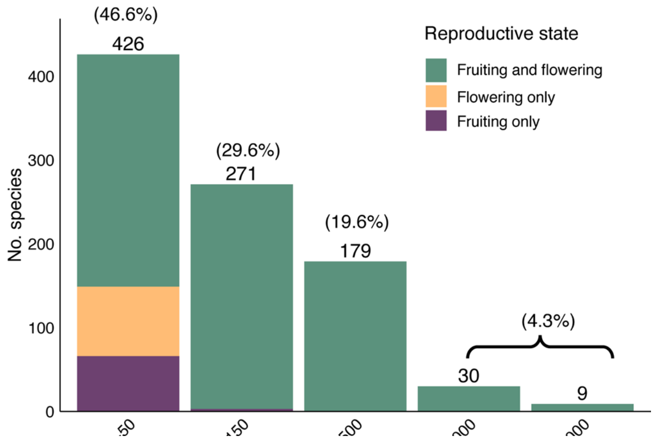

Figure 6. Taxonomic histogram (per species) by total observation counts in the integrated phenology dataset. Numbers and % above bars indicate species counts and the percentage of species this represents in each observation frequency category.

in the context of climate change. Records from both contemporary and historical periods (e.g. pre-industrialisation) can improve modelling of species' responses to environmental change. Studies documenting phenological changes in temperate systems (Greve et al. 2016, Davis et al. 2022b) have relied on similar historical baselines to distinguish anthropogenic from natural variation in plant phenology. While such baselines remain largely absent for subtropical systems, our data integration approach shows that opportunities exist to establish them. There was notably better temporal coverage, but extending sampling to pre-industrial periods remains a challenge. For example, only 19 species had more than 150 observations between 1770 and 1970, whereas 73 species reached this threshold between 2001 and 2025. Despite this, the lack of phylogenetic signal demonstrates that the data represent broad taxonomic coverage and exemplify the utility of data integration. Each additional source offered unique taxonomic observations (e.g. expert photographic collections contributed 59 unique species between 1971 and 2000) or enhanced temporal or spatial sampling extent, demonstrating that species-level research opportunities are improved through data integration.

A key innovation of our approach was engagement with expert botanists through non-academic networks to access unpublished or informal datasets that are rarely incorporated into phenological syntheses. Expert photographic collections, unpublished field notes, and seed collection records contributed 23 271 observations across 740 species. Notably, these non-traditional sources identified 46 species not found in any other data source, highlighting their enormous value. An important insight was the integration of non-research-purpose data, such as seed collection records, which contributed 4617 fruiting observations and six unique species. There are, however, challenges both in data discovery, data availability and sharing, as well as the time required for digitisation and standardisation. We partially overcame this challenge by leveraging easily accessible machine learning computer vision models for images; however, a high level of programming expertise is still required to effectively utilise these approaches. In our case, engagement outside of academic and open-source repositories proved crucial.

Data integration has broad applicability beyond the combinations of herbarium and citizen science observations that dominate current phenological research. Our multi-source approach extends these methods to demonstrate systematic complementarity across six diverse data types, aligning with recent advances that show value in combining herbarium specimens with contemporary data (Ellwood et al. 2019, Miller et al. 2021, Yoder et al. 2024). However, the success of this expanded approach depends on existing herbarium infrastructure, active expert networks, the researcher's willingness to build relationships that facilitate data sharing, and sufficient botanical observations to generate these diverse data streams. These conditions are likely met in regions with colonial botanical histories, including Australia and other Southern Hemisphere areas, as well as tropical and subtropical regions. Therefore, we foresee that similar data integration in the other areas can identify and leverage expert networks and unconventional data sources.

Despite revealing substantial research capacity, our integration approach operates entirely within Western scientific knowledge systems and reflects the colonial history of data collection in Australia. Although indigenous knowledge systems are increasingly recognised in ecological research, significant barriers remain to meaningful ecological relationship-building across diverse knowledge systems. Indigenous knowledge of multi-year and seasonal patterns, species interactions, and long-term environmental change represents millennia of systematic observation that could fundamentally enhance our understanding of phenology. We must acknowledge the complex sociopolitical contexts from which many of the sources included in this synthesis arise. For example, herbarium specimens exemplify extractive practices with complex colonist history (Park et al. 2023a). In Australia, early colonist explorers collected species and observations under the guidance, either voluntarily or through coercion, of local Indigenous peoples; yet this knowledge is recognised only for how it served to further the colonist agenda (Hartmann 2015). To move beyond this extractive colonist legacy, phenological research requires collaborative approaches that value and recognise Indigenous research priorities and knowledge sovereignty.

Our synthesis demonstrates how collaborative integration can unlock new research opportunities in data-sparse systems. The 255-year temporal span enables the establishment of phenological baselines and the historical benchmarks necessary for detecting climate-driven changes. While many poorly represented species likely reflect a legacy of extensive land clearing that preceded systematic botanical monitoring, our results suggest that integration approaches may provide the only available phenological information for species in heavily modified landscapes. The taxonomic breadth (915 species) and temporal depth enable investigation of plant–animal interaction networks, including phenological hypotheses within the context of climate change. For example, the influence of pollination strategy and seed dispersal method on reproductive frequency may help identify phenological mismatches. The value of integration extends beyond simple observation counts; increased temporal span and geographic coverage will benefit data-sparse species. To fully realise this potential, we call for coordinated efforts to develop integration methodologies, systematically engage expert networks, and establish data-sharing frameworks that can unlock phenological research capacity in data-sparse systems, while prioritising collaborative approaches that value multiple knowledge systems.

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Author contributions

Ella Cathcart-van Weeren: Conceptualization (lead); Data curation (lead); Formal analysis (lead); Investigation (lead); Methodology (lead); Project administration (lead). **John M. Dwyer**: Supervision (supporting); Writing – review and editing (equal); Data curation (supporting). **Brian Hawkins**: Data curation (supporting). **Jennifer Holmes**: Data curation (supporting). **Glenn Holmes**: Data curation (supporting). **Glenn Leiper**: Data curation (supporting). **William McDonald**: Data curation (supporting). **Matthew Mo**: Data curation (supporting). **Hugh Nicholson**: Data curation (supporting). **Rob Price**: Data curation (supporting). **Karen Shaw**: Data curation (supporting). **Spencer Shaw**: Data curation (supporting). **David Waterhouse**: Data curation (supporting). **Lui Weber**: Data curation (supporting); Writing – review and editing (supporting). **Matthew S. Luskin**: Conceptualization (supporting); Methodology (supporting); Supervision (equal); Writing – review and editing (equal).

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Data availability statement

Data are available from the Dryad Digital Repository: https://doi.org/10.5061/dryad.gtht76j1m (Cathcart-van Weeren et al. 2026).

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