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The PeatPic Project: Predicting plot-scale peatland green leaf phenology across global peatlands

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Abstract

Peatlands store approximately one-third of the world's soil carbon (C), but their functioning is highly variable at small spatial scales due to differences in vegetation cover and environmental conditions such as water table depth. This fine-scale heterogeneity plays a key role in carbon dynamics yet capturing it—particularly in relation to green leaf phenology—is challenging with traditional remote sensing methods. To address this, we developed a smartphone-based methodology and community-science project called the PeatPic Project. We gathered over 3700 photographs from 27 sites across 10 countries in 2021 and 2022, representing different peatland types (bog, fen, and swamp), at 1–2-week intervals. We calculated green leaf phenology (GLP) metrics, such as the data of the start of the season and end of the season, based on the red-blue-green bands from these photographs. We found that GLP metrics, such as day of year at peak greenness, varied significantly across peatland types and dominant vegetation communities, with peak greenness at bog sites occurring approximately 10 days later in the year compared to fen sites. Furthermore, variables relation to peatland/vegetation type and energy balance were key predictors of peatland green leaf phenology. The PeatPic Project's readily available methodology offers low-cost opportunities for further research into peatland phenology, enabling the calculation of additional phenological indices and integration with other data types. By refining our understanding of peatland green leaf phenology, we can improve predictive C modelling and better assess the impacts of future changes on these important ecosystems.

1. Introduction

Peatlands are a type of wetland ecosystem with a thick layer of partially decomposed organic matter. They cover approximately 400 million hectares (~3 %) of the world's surface but store disportionately large amount of the world's soil carbon (C) – estimated at ~600 Gt of C, or 21% of the total global soil C stock (Page et al. 2011; Scharlemann et al. 2014; Yu, 2012). Their ability to store such large amounts of C means that peatlands have the potential to significantly influence the climate-C cycle feedback (Moore et al. 1998), act as a nature-based solution to climate change (Strack et al. 2022; Girkin and Davidson, 2024), and influence global C budgets (e.g., Saunois et al. 2024). To understand peatland roles in local and global C cycling, there has been increased focus on investigating peatland functioning, particularly in relation to interactions between hydrological conditions and C storage (van Bellen and Larivière, 2020). However, less attention has been directed to understanding how peatland vegetation communities' function with regards to green leaf phenology (GLP: the phenology of leaf traits, e.g., timing of leaf out, timing of peak greenness and leaf fall) which is an important driver of terrestrial C cycling (Hufkens et al. 2012).

Changes in temperature and precipitation patterns are altering phenological events in peatlands, potentially affecting their C sequestration capacity (Koebsch et al. 2020; Davidson et al. 2021; Simpson et al. 2025; Köster et al, 2023). For example, increasing global air temperatures are leading to substantial changes in the timing and duration of ecosystem processes, including plant green-up in the spring and senescence in the autumn (Schädel et al. 2023), and an overall lengthening of the growing season in many regions (Collins et al. 2021; Richardson et al. 2018). However, these investigations typically focus on ecosystem-scale phenology, where trends in tree-dominated systems may overshadow the dynamics of low-statured understory species (e.g., mosses, shrubs, and graminoids), which dominate peatland productivity in many northern sites. While small statured, these plants can often dominate net primary productivity budgets in peatlands (e.g., Griffiths et al. 2017). Thus, the green leaf phenology of understory plants and its variation across northern peatlands remains elusive.

Changes in green leaf phenology can have significant impacts on net annual C uptake (Koebsch et al. 2020; Hanson et al. 2020; Simpson et al. 2025). Early leaf-out and extended growing seasons may increase C uptake but also result in higher C release during dry periods (Hanson et al. 2020). Moss-dominated peatlands, such as bogs, generally green up more slowly than graminoid- and shrub-dominated peatlands (e.g., fens), resulting in lower photosynthetic activity earlier in the growing season and impacting C cycling rates through faster C turnover (Blodau, 2002; Peacock et al. 2019). Slow-growing *Sphagnum* mosses can lengthen the growing season in peatlands, extending C sequestration further into the autumn period (Kivimäki et al. 2008). Different vascular plant species can also be physiologically active at various times of the year, with knock-on effects on C source/sink behaviour (Ström et al. 2005). The changes in growing season length have also been linked to peat accumulation rates (Gallego-Sala et al. 2018), suggesting that understanding how plant communities green-up and growing season lengths vary in space and time (and how they are changing in response to climate change) is critical to monitoring long-term peatland C storage (Charman et al. 2013). Disturbance impacts on peatland vegetation can also alter greenness trajectories, through both changes in the greenness timing of the vegetation present, as well as shifts within the community that can lead to different greenness characteristics compared to the previous undisturbed community (Davidson et al. 2021). Thus, the impacts of global change processes on peatland phenology are highly uncertain but likely to be dependent on peatland type, climate, disturbance regime, and other factors.

Digital Red-Green-Blue (RGB) photography is a non-destructive method that can be used to measure and understand plant GLP (Crimmins & Crimmins, 2008). Photographs provide visual evidence and detailed records of phenological events in an easily accessible, standardisable, and low-cost manner. They allow for the verification and calibration of observational data and improve accuracy (Barve et al. 2020) including within prediction and estimation of plot-scale C fluxes (Gutekunst et al. 2019; Davidson et al. 2021). There have been ecosystem scale studies looking at peatland vegetation GLP (Peichl et al. 2015; Koebsch et al. 2020) using high temporal resolution image archives and studies synthesizing data from networks such as Phenocam (Wingate et al. 2015; Richardson et al. 2018) but there are very few plot-scale studies looking at peatland vegetation GLP (Peichl et al. 2018; Davidson et al. 2021; Garisoain et al. 2023). Peatlands are inherently heterogeneous, including a variety of peatland microforms and vegetation communities, associated sub-meter changes in C flux (Riquelme del Río et al. 2024), that vary in their response to changing water table and temperature regimes (Strack and Waddington, 2007; Munir et al. 2015). Thus, understanding small-scale (≤1 m^2) resolution of peatland GLP is key to monitoring and predicting peatland functional changes.

Therefore, there is a need for a comprehensive global network of datasets to understand the spatial and temporal variations in peatland GLP at the square-meter scale, to provide a baseline for long-term monitoring to track global change effects. Advances in smartphone technology and online platforms have facilitated the widespread collection and sharing of phenological data through photographs (Hufkens et al. 2019; Barve et al. 2020; Tonnang et al. 2020; Liu et al. 2022). This method thus provides a promising avenue for peatland GLP research, and one particularly well suited to both community science due to the readily available nature of smartphones (Klinger et al. 2024) and advances in image processing driven by machine learning algorithms (Fang et al. 2019; Reichstein et al. 2019).

Here, we use a standardised smartphone photography method and a community science approach (the PeatPic Project) to investigate how peatland greenness trajectories, specifically, day of year at peak greenness, varies across different peatland types. Additionally, we test for site characteristics and environmental factors as predictors of GLP. We hypothesize that 1) graminoid- and shrub-dominated systems peak in greenness earlier than moss dominated systems, 2) peak greenness will be earlier in warm climate peatlands compared to cool climate and 3) peatlands at lower latitudes (are expected to reach peak greenness earlier than peatlands at higher latitudes.

2. Methods

2.1 Community photographs

During 2021 and 2022, we recruited project participants via email, social media, and word of mouth amongst the peatland research community. Participants collected plot-scale (0.036 to 1 m^2) photographs of the dominant vegetation communities at their peatland research sites (Figure 1) using the standardised PeatPic protocol developed by the project lead (see Supplementary Information for details).

All sites had between 4-12 plots. Plots were either permanent locations for monitoring vegetation or measuring C fluxes (e.g. collars), or were temporarily marked using quadrats, flags or other markers (examples for each site shown in Figure S1). Photographs were collected on a weekly to bi-weekly basis across most sites, dependent on remoteness and logistics, and at all sites photography began before the growing season and continued into the autumn senescence period where logistically possible. Participants were required to have the image acquisition mode set to auto white balance and autofocus, photograph under as clear or overcast sky conditions as possible and to avoid including any shadows in the photo where possible. Photographs were consistently taken from a nadir angle (directly overhead), approximately 1 m above the ground-layer canopy. While different camera/phone sensors were used across sites, for a given site, only one phone or camera type was used.

Alongside the photographs, participants were asked to provide information on the peatland type (bog, fen or swamp), the dominant vegetation community (*Sphagnum*-, feather moss-, graminoid- or shrub-dominated), the microform type (hummock, lawn or hollow), whether the site had tree cover (at site level), whether it was underlain by permafrost (at plot level), and whether there was any evidence of disturbance impact (at plot level).

2.2 Red-Green-Blue photography analysis

We used the R package *Phenopix* version 2.4.4 (Filippa et al. 2016) to calculate the greenness index:

$$Greenness\ index = G_{DN} / R_{DN} + G_{DN} + B_{DN} \qquad \text{Eq. 1}$$

where the R_{DN}, G_{DN} and B_{DN} are the average red, green and blue digital numbers respectively. This index was chosen as it is more robust than other indices with regard to scene illumination and shadows (Sonnentag et al. 2012; Davidson et al. 2019). Any photos that included snow cover or standing water were omitted from the analysis (approximately 0.2% of the total number of submitted photographs).

We used the R package's *DrawROI* function to hand-identify and delineate a Region-Of-Interest of the dominated vegetation community within the designated plot in each photograph. We then used its *ExtractVIs* function to calculate the index on a per-pixel basis (Toomey et al. 2015). To compare the seasonal trajectories of the greenness indices between the different peatland types and four vegetation community groups, we fitted a Gaussian model to our measured greenness values by day of the year (DOY; Davidson et al. 2021). We used the following model to fit data at each unique plot for each year (hereafter, plot-year):

$$Modelled\ greenness\ index = a\ x\ e^{-0.5}[DOY - \frac{b}{c}]^2 \qquad \text{Eq. 2}$$

where *a, b and c* are parameters describing the seasonal trajectory of the greenness index; the peak value (a), DOY at peak greenness, (b) and the growth rate of the curve (c). The parameters allowed us to compare the peak, timing of peak, and progression of GLP across all plots. We focus primarily on the DOY at peak greenness as a descriptor of changes to GLP patterns because sites varied in their specific phone or camera sensor and their greenness values would not be comparable. However, the trajectory of greenness within a site and day of peak value are comparable. For calculating the day of peak greenness, we only used model outputs from eq. 2 when p-value <0.05. Out of our total 319 plot-years where we fit the eq. 2 model, we had to remove 96 unique plot-years because their model fit p-value was >0.05. Note that to standardize comparisons of southern and northern hemisphere growing seasons, we adjusted the southern hemisphere DOYs by adding 182.5 to any DOY less than 182.5 and by subtracting 182.5 from any DOY greater than 182.5. This allowed for an alignment of the growing season trajectories in both the hemispheres that was necessary for fitting eq. 2 to the data.

2.3 Predictor data

For predictor data, we used a range of site-reported peatland characteristics and climate reanalysis data from ERA5 (Muñoz Sabater 2019; Download date February 18, 2025). The resolution of the ERA5 data is 0.25° x 0.25°. We downloaded monthly averaged data (from hourly data) for the years of our photographs (2021 and 2022) for the entire globe and extracted the data for the pixel in which our sites occurred using the *terra* R package (Hijmans 2024). We extracted variables related to our hypotheses (Table 1), namely, snow depth, snow albedo, soil and air temperature, incoming solar radiation, surface sensible and latent heat flux, soil moisture, and precipitation. We then averaged all the months within 2021 or 2022 to obtain an annual average value for each site and year. The only exception was precipitation, which we summed instead of averaged. Note that our precipitation metric is monthly averaged precipitation (based on what the ERA5 product provides) summed annually for the measurement year (2021 or 2022).

2.4 Data analyses

All analyses were performed using R version 4.4.2 (R Core Team, 2024). We conducted Kruskal-Wallis tests to examine differences between categories, for example, to compare mean DOY at peak greenness values across our three peatland types and vegetation communities. This was followed by pairwise comparisons using a Steel-Dwass post-hoc test to determine significant differences between individual peatland types and vegetation communities. Statistical significance was set at $p < 0.05$ for all tests.

We implemented Generalised Additive Mixed Models (GAMM) in R using the *mgcv* package (Wood, 2011) to determine the best predictors of peak greenness. We selected GAMM because it accommodates non-linear relationships between predictors and response variables, while also allowing for random effects to account for hierarchical structure and repeated measurements in the data. To minimise overfitting and multicollinearity, we first reduced the full set of environmental covariates (see Table 1) by selecting the representative and least collinear variables. We applied a hierarchical clustering approach using the *ClustOfVar* package (Chavent et al. 2012), which grouped variables into four main clusters based on shared variance (Figure S2). To explore model performance across combinations of predictors, we ran 1,000 GAMM iterations. In each iteration, we randomly selected one variable from each of the four clusters to include fixed effects, while treating year and camera type as random intercepts to account for temporal and equipment variability. This approach allowed us to address potential issues with multicollinearity, repeated measures, and overparameterization. Each model was trained on 70% of the data (Training set) and evaluated on the remaining 30% (Test set) of the data to test model predictive performance. We then quantified the predictive performance of each model iteration by computing the coefficient of determination (R^2) from predicted versus observed greenness peak values in the Test set. Finally, we selected the best-performing GAMM across the 1,000 iterations (highest Tes-set R^2) and used its four selected covariates to fit a final GAMM to the entire dataset. Our 1,000 GAMM iterations had relatively good predictive strength, with a mean cross-validation of $R^2 = 0.18 \pm 0.13$. Finally, we used the function *gam.hp* to assess the partition of variance explained by each predictor in our best GAMM model.

Table 1. Predictor variables included in the Generalized Mixed Effects Additive Models (GAMM).

Name	Description	Units	Source	Rationale for using as predictor
Latitude	Geographic coordinate specifying the north-south position of the site	Degrees (°)	Site PI reported	Determines climatic zone and seasonal patterns, affecting the timing of peak vegetation greenness.
Permafrost Presence	Indicates whether permafrost is present at the site	Binary (Y/N)	Site PI reported	Permafrost affects soil temperature and moisture regimes, influencing plant root systems and the timing of peak vegetation greenness.
Disturbance	Indicates whether disturbance is present at the site	Binary (Y/N)	Site PI reported	Influences a variety of plant growth factors, including phenology
Tree cover	Indicate whether peatland had a dominant cover of trees or was open	Binary (Y/N)	Site PI reported	Influences understory plant community characteristics
Peatland type	Indicates what type of peatland the plot was in	Bog, fen or swamp	Site PI reported	Linked to site hydrology and nutrient status, which influence plant phenology

Dominant Vegetation type	Indicates the dominant vegetation type in the plot	Shrub, *Sphagnum*, feather moss or graminoid dominated	Site PI reported	Plant taxonomic groups have varying phenological traits
Microform	Indicates where plot was located on the landscape	Hummock, hollow or lawn	Site PI reported	Influences a variety of plant growth factors, including phenology
Mean annual air temperature	Annual average air temperature at the site	Degrees Celsius (°C)	Climate reanalysis (ERA5)	Influences the length of the growing season and the timing of vegetation development, affecting when peak greenness is achieved.
Mean annual soil temperature	Annual average soil temperature at the site	Degrees Celsius (°C)	Climate reanalysis (ERA5)	Affects root growth, nutrient uptake, and soil microbial activity, which are critical for plant health and the timing of peak vegetation greenness.
Annual precipitation	Total annual rainfall received at the site	Millimetres (mm)	Climate reanalysis (ERA5)	Determines soil moisture levels, influencing plant growth cycles and the timing of peak greenness.
Volumetric Soil Water Content	Water content in the soil within the 0-7 cm layer	Cubic meters per cubic meter (m^3/m^3)	Climate reanalysis (ERA5)	Impacts plant moisture and nutrient availability, affecting the timing of peak vegetation health.
Snow Albedo	Reflectivity of snow cover at the site	Dimensionless (0-1)	Climate reanalysis (ERA5)	Influences soil temperature and moisture by affecting the amount of solar radiation absorbed, thereby impacting the start and peak of the growing season.
Snow Depth	Thickness of snow cover at the site	Meters (m)	Climate reanalysis (ERA5)	Affects the duration of snow cover, which can delay or advance the onset of the growing season and influence the timing of peak greenness.
Surface Net Solar Radiation	Net solar energy received at the ground or water surface	Joules per square meter ($J\ m^{-2}$)	Climate reanalysis (ERA5)	Determines the energy available for photosynthesis, influencing plant growth rate and the timing of peak vegetation.
Surface Latent Heat Flux	Energy transfer associated with phase changes of water at the surface	Joules per square meter ($J\ m^{-2}$)	Climate reanalysis (ERA5)	Influences soil moisture and temperature regulation, affecting plant growth cycles and peak greenness timing.
Surface Sensible Heat Flux	Energy transfer related to temperature changes at the surface	Joules per square meter ($J\ m^{-2}$)	Climate reanalysis (ERA5)	Affects microclimatic conditions, influencing plant metabolism and the timing of peak vegetation greenness.

3. Results

3.1 Description of collected data

In total, over 3,700 photographs (2433 in 2021 and 1306 in 2022) were contributed to this project from participants across 164 unique plots distributed among 27 different sites in 10 different countries (Figure 1/Table S1). Most photographs were collected from bogs (11 open and 3 with trees) and fens (8 open and 4 with trees), with one swamp site (Figure S3). Four sites had photographs for both 2021 and 2022 (Bonanza Creek, Cloncrow, Degerö and Senda Darwin). In our dataset, plots were distributed across various vegetation types, microforms, permafrost presence, and tree cover. The majority of data come from graminoid-dominated (33%), shrub-dominated (18%), and sphagnum-dominated (17%) plots. Plots with permafrost present comprise 23% of the data, while treed plots comprise 6% of the data. Regarding microforms, hummocks account for 24% of the data, lawns for 18%, hollows for 11%, while the rest are not specified. Disturbances included historical or modern, e.g. drainage, grazing, oil and gas exploration activities and wildfire. Individual plot greenness values per site are shown in Figure 2 and the mean ± SE greenness values for plots across all 27 sites, averaged by day of year, is shown in Figure 3. The remaining results focus on our key phenology metric, DOY at peak greenness, that we calculated for each unique plot-year (Methods in section 2.2).

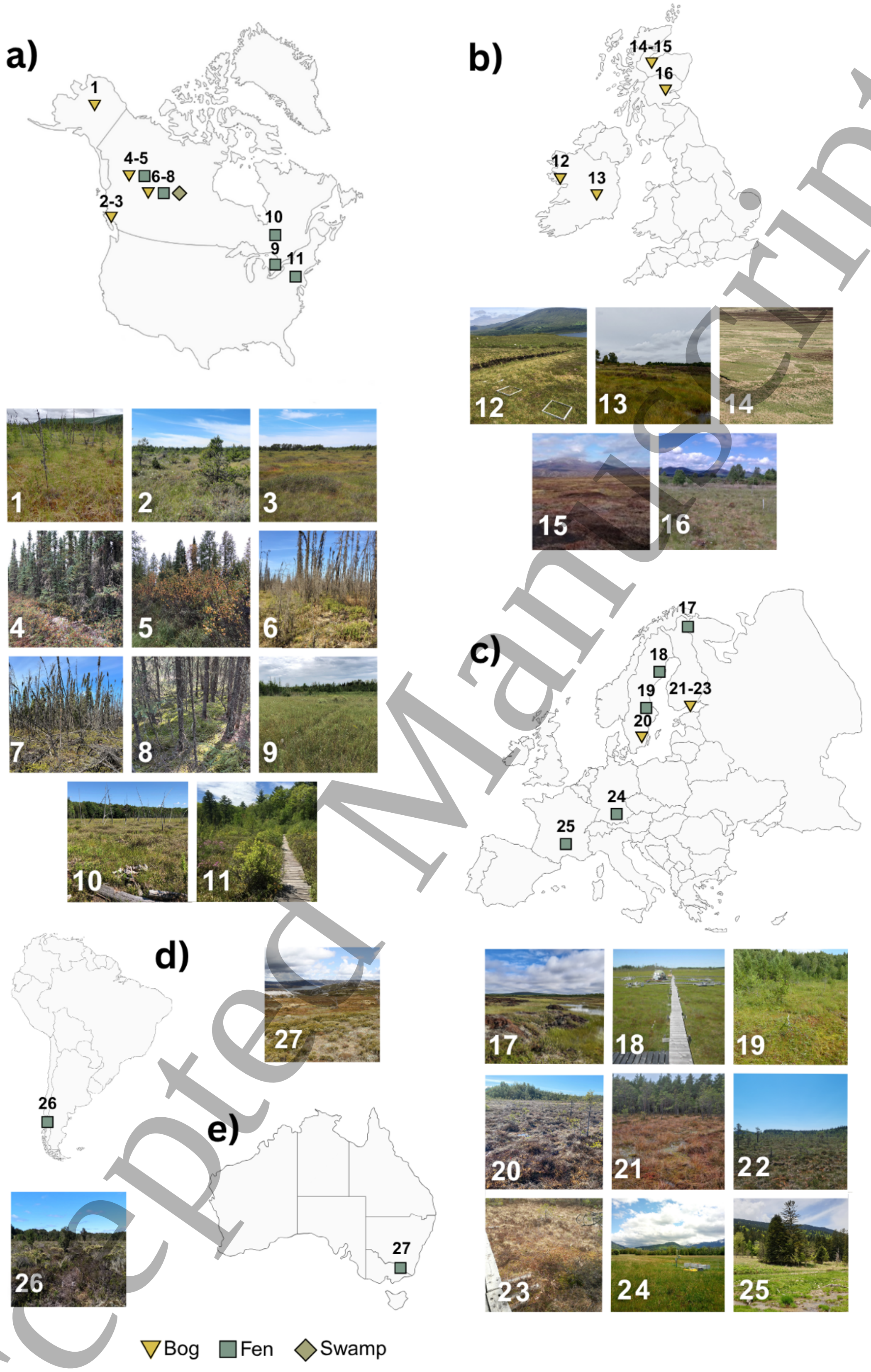

Figure 1. Location and photographs of study sites: 1) Bonanza Creek (*), 2) Burns Bog 1 (*), 3) Burns Bog 2 (*), 4) Harmon Valley (*), 5) Harmon Valley (**), 6) Poplar (**), 7) Prairie Creek (*), 8) Heaven (***), 9) Fletcher (**), 10) Sprucedale (**), 11) Sallie's Fen (**), 12) Burrishoole (*), 13) Cloncrow (*),

14) Ladderfoot (*), 15) Blackburn (*), 16) Leadburn Wood (*), 17) Iškoras (**), 18) Degerö (**), 19) Sjödyn (**), 20) Våxmossen (*), 21) Isosuo (*), 22) Tervalamminsuo (**), 23) Slåtmossen (**), 24) Benediktbeuern (**), 25) Counozouls (**), 26) Senda Darwin (**) and 27) Heathy Spur (**). ** Indicates bog, ** indicates fen and *** indicates swamp*. Note where site names are duplicated (i.e. Burns Bog, Harmon Valley), these represent two distinct sub-sites with different conditions (e.g., different vegetation communities, different experimental manipulations, different disturbance histories). All photographs provided by co-authors.

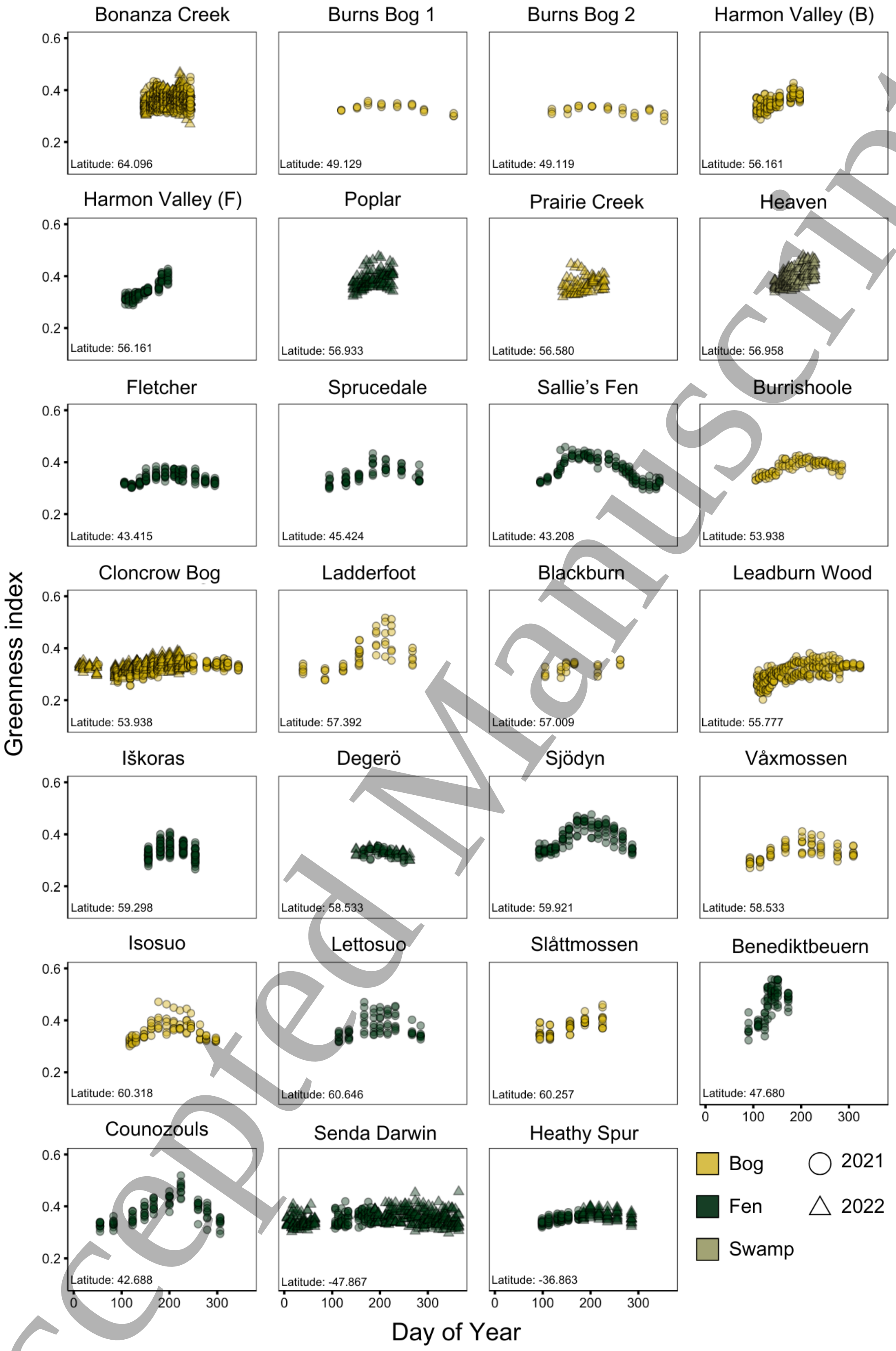

Figure 2. Raw greenness index values for all 27 sites across peatland types. Each point represents an individual plot. Day of year adjusted for both southern hemisphere sites (Senda Darwin and Heathy Spur). Circles represent data collected in 2021 and triangles represent data collected in 2022. Four

sites collected photographs for both years of the study (Bonanza Creek, Cloncrow Bog, Degerö and Senda Darwin). Note that our gaussian fits on these data were done on the unique plot-level and not on site-level (see eq. 2 in methods).

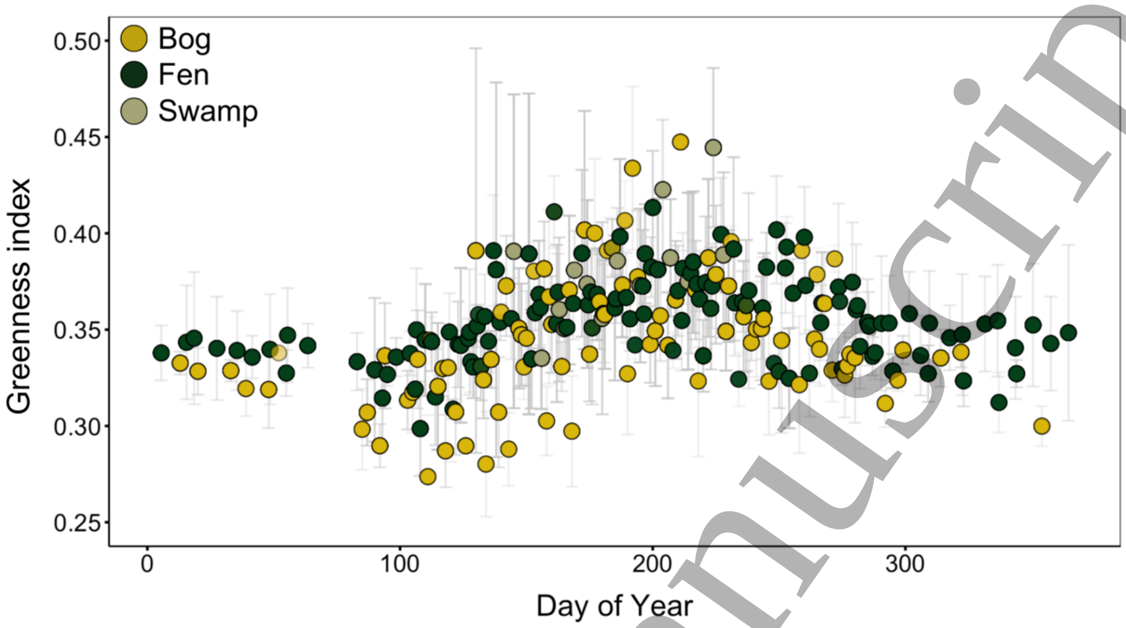

Figure 3. Mean ± SE greenness index for plots across all 27 sites (coloured by peatland type, bog n = 145, fen n = 154 and swamp n = 14), averaged by day of year. The southern hemisphere day of the year has been adjusted to match the northern hemisphere (see Methods).

3.2 Variability in green leaf phenology

Day of year at peak greenness was significantly different between peatland types (Figure 4A; Chi-square = 34.2; $p < 0.0001$), indicating bog and fen are phenologically significantly different ($Z = -5.07$, $p < 0.0001$). Bog sites had a wider range, with peak greenness occurring a median of 10 days later in the year compared to fen sites. Note that the swamp greenness data were only from one site (Davidson et al. 2024). Peak greenness also varied among vegetation types (Figure 4B; Chi square = 10.91; $p = 0.012$) with *Sphagnum*- and graminoid-dominated plots showing significant differences ($Z = -3.16$, $p = 0.0016$). Contrary to our hypothesis, graminoid-dominated plots peaked in leaf greenness approximately one week later than *Sphagnum*-dominated ones.

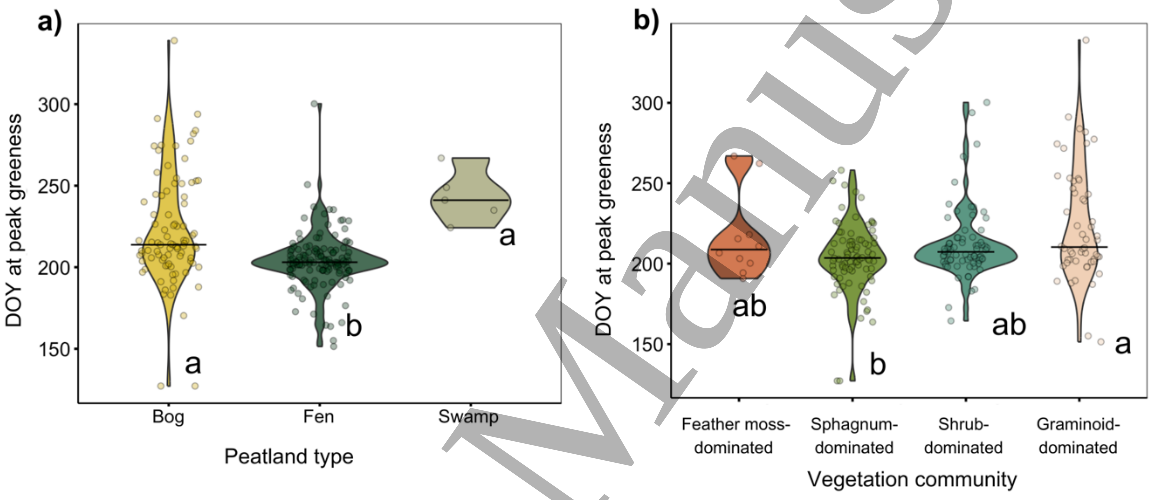

Figure 4. a) Day of year (DOY) at peak greenness for all three peatland types (each point represents a different plot) and b) for all four vegetation community types. Horizontal black bars indicate the median day of year. Lowercase letters indicate significant differences between categories (Kruskal-Wallis and pairwise comparisons using a Steel-Dwass post-hoc test. Statistical significance was set at $p < 0.05$ for all tests).

3.3 Predictors of green leaf phenology

The best GAMM had a very good predictive strength with $R^2 = 0.40$ and a deviance explained at 48%. The dominant site characteristics-related predictors of DOY at peak greenness across our sites were vegetation (16% of total deviance explained) and peatland type (21% of total deviance explained) (Figure 4 and 5A). Furthermore, surface net solar radiation (46% of total deviance explained) and latitude (17% of total deviance explained) were the most important factors driving green leaf phenology across peatlands (Figure 5A-C). As per our hypothesis that peak greenness will be earlier in warm sites compared to cool sites, we found that DOY at peak greenness strongly decreased with increasing surface net solar radiation (Figure 5C). Similarly, we had expected that DOY at peak greenness would increase going from equator to poles, but this trend was nonlinear, and our results did not support our hypothesis (Figure 5B), while noting the difference in site distribution along latitude.

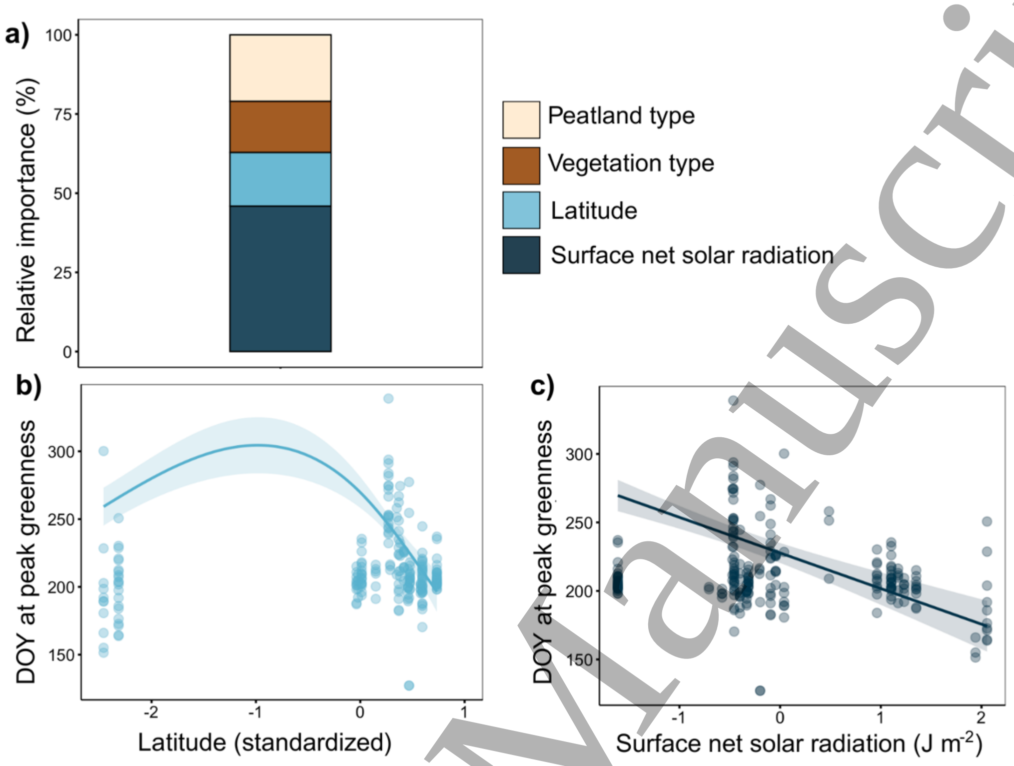

Figure 5. A) Variance partitioning modelling evaluating the portions of variation in green leaf phenology and response of day of year (DOY) at peak greenness to B) changing latitude and C) surface net solar radiation. The y-axis indicates the relative influence of the explanatory variables on the prediction based on partial residuals from the GAMM. Shaded area shows a 95% confidence interval while the line shows the smooth or linear trend. All continuous environmental variables shown were standardised before GAMM model fitting. The partial effects (y-axis) reflect these standardised scales (x-axis).

4. Discussion

Here, we investigated climatic, environmental and vegetation controls on peatland plant community green leaf phenology (GLP) using photographs collected via a community science approach.

4.1. Drivers of peatland GLP

Overall, our model explained 48% of variation in peak greenness, indicating that peatland type, vegetation type, latitude and surface solar net radiation are the strongest predictors of DOY at peak greenness. The variation in DOY at peak greenness was larger in bogs than in fens (Figure 4A), likely linked to the dominant plant species present. Linked to the strong control of peatland type on GLP, differences in vegetation composition across latitudes also influence GLP. The dominant species in the bog sites in this study, (Sphagnum mosses – Figure S3), often have slower growth rates and delayed phenological phases, such as leaf emergence and senescence (Garisoain et al. 2023), resulting from lower nutrient availability (Aerts et al. 1992). Bog species are adapted to these nutrient poor-conditions and exhibit conservative growth strategies (Laine et al. 2021), including prolonged periods of leaf retention while having reduced rates of photosynthesis (Huth et al. 2021), meaning they may stay ‘greener’ or more productive for longer than other peatland types. However, our bog or fen sites were not strictly *Sphagnum* or graminoid dominated as we had expected. Instead, both site types had a mix of different dominant vegetation which may explain this variability (Figure S3). Additionally, Sphagnum communities may not appear ‘green’ when productive due to either species present or location on landscape (hummock vs. hollow for example) (Letendre et al. 2008). Contrary to our hypothesis, we observed that *Sphagnum*-dominated plots green up earlier than graminoid-dominated plots. This could be in part due to the range of climates that the *Sphagnum*-dominated plots spanned, alongside the moss already being green when the snow disappears in comparison to vascular plants that need more time to develop their green biomass.

The typically higher pH and nutrient availability of fens means they support not only a wider diversity in plant species but are primarily dominated by species that favour more rapid growth characteristics i.e., sedges and non-ericaceous shrubs such as *Salix* spp., with different phenological timing. These species often display earlier leaf-out in spring compared to more moss-dominated peatlands (Leppälä et al. 2008) and faster cycles of growth, senescence, and productivity (Davidson et al. 2021). Species-specific phenological responses to changing environmental conditions and photoperiods may also vary between peatland types (Peichl et al. 2018). For example, sedge-dominated fens may exhibit greater sensitivity to air/soil temperature fluctuations and extensions to the growing season, promoting earlier green up (Thayamkottu et al. 2024).

Although disturbances such as permafrost thaw or tree cover were not found to be significant controls on plot-scale GLP in this study (likely due to limited replication of permafrost versus non-permafrost peatland or treed versus non-treed peatland sites), these variables could still impact peatland GLP. For example, permafrost thaw could substantially alter peatland GLP by modifying hydrological conditions, soil thermal regimes, and nutrient availability (Keuper et al. 2012), thereby affecting plant growth timing and duration. As the permafrost degrades, increased active layer thickness and altered water tables may favour species with different phenological strategies, reshaping community-level GLP patterns. Additionally, vegetation structure, particularly tree cover, could also play a critical role in mediating GLP. Davidson et al. (2021) demonstrated that the removal of tree cover in boreal peatlands following oil and gas exploration disturbances led to a reorganization of the entire vegetation community, rather than a direct alteration of phenology alone, suggesting that GLP responses are often emergent properties of broader community shifts rather than isolated trait-level changes.

As per our hypothesis, warmer sites greened earlier than cool sites, as indicated by surface net solar radiation having a strong influence on DOY of peak greenness. Surface net solar radiation determines the energy available for photosynthesis and thermal regulation, thereby influencing the onset, intensity, and duration of peak peatland vegetative activity (Leonard et al. 2021; Gu et al. 2023). Earlier peak greenness often coincides with increased springtime radiation inputs, enhancing photosynthetic efficiency and promoting early canopy development (Ren et al. 2024). Variability in the DOY of peak greenness at our sites will affect plant productivity and community dynamics, especially in peatlands across northern latitudes, where vegetation is especially sensitive to microclimatic conditions and water availability (Walther et al. 2018). Shifts in solar radiation regimes due to climate change could therefore alter the phenological trajectory and ecological functioning of peatland systems over time (Antala et al. 2022).

Our hypothesis that DOY at peak greenness would be later going from equator to poles was not supported. Our results indicate that DOY at peak greenness was earlier in the northern peatland sites (Alaska, northern Canada, Norway and Finland) compared to mid-latitude sites such as the UK or southern Sweden. Alongside the controls on vegetation types present in these peatlands, latitude can also play a critical role through its influence on photoperiod, temperature regimes, and growing season length (Koebsch et al. 2019). At higher latitudes, extreme seasonal variation in day length exerts a strong control on phenological events (Collins et al. 2021), with long photoperiods in summer promoting rapid canopy development and short autumn days triggering earlier senescence (Estiarte & Peñuelas, 2014). In these regions, temperature constraints often delay spring green-up due to prolonged snow cover and cooler soil temperatures, while early frosts can prompt premature leaf senescence, leading to a compressed growing season (Bigler & Bugmann, 2018).

In contrast, the lower-latitude sites may experience milder climates with longer and more stable growing seasons (Hudson et al. 2022). These conditions will allow for earlier leaf emergence and extended periods of vegetation greenness, potentially supporting multiple growth peaks depending on hydrological conditions as found in forest ecosystems by Denham et al. (2023). At the plot scale, local microtopographic variation (e.g., hummocks versus hollows) can modulate these latitudinal effects by altering soil temperature, water table depth, and light availability (van der Molen et al. 1994; Villa et al. 2019), leading to spatial heterogeneity in phenological patterns even within a single site.

4.2. A low-cost method and peatland GLP database using smartphone photography

Using a standardised, community science approach, we collected over 3,700 photographs of peatland vegetation at the plot/microform level from a diverse array of sites. Our analysis demonstrates that smartphones are capable of tracking peatland phenology by capturing variations in greenness index across changing seasons. Such plot-scale phenology, particularly for the small-statured keystone peatland species such as *Sphagnum*, cannot be observed using more traditional, satellite-based methods (Hufkens et al. 2019). Although advances in unmanned aerial vehicle (UAV) technology means high resolution imagery (< 5 cm) can be collected for these vegetation communities, it is still likely to be more costly and time-consuming than using the smartphone methodology we present here. We therefore recommend using a combination of these methodologies at different scales. Furthermore, connecting GLP using this readily available methodology to other time series data such as eddy covariance-based measurements of net ecosystem exchange could also help upscale phenology at sites that do not have eddy covariance towers but have resources for photo-based analyses as a low-cost alternative to the Phenocam platform (Richardson et al. 2018). Our analysis focuses on spatial differences across sites, but with future additional data, our database can enable a better understanding of interannual variability in phenology at sites and on-going response to climate warming.

Peatlands have been subject to widespread historical (Fluet-Chouinard et al. 2023) and ongoing (Page et al. 2022) drainage and degradation, rewetting and restoration (Andersen et al. 2017), grazing (Valdés-Barrera et al. 2019), climate disturbances such as warming (Muller and Joos 2021) and permafrost thaw (Varner et al. 2022). Long-term monitoring is key to understanding how these perturbations affect peatland functioning, but this is typically expensive and difficult to implement (Minasny et al. 2023). Smartphone photographs offer a viable, low-cost and simple method that can be used by researchers, practitioners, and community scientists alike, to track these long-term changes by recording GLP. Furthermore, GLP can be directly related to peatland C flux (Peichl et al. 2015; Järveoja et al. 2018; Davidson et al. 2021) and thus this method could be combined with methods that offer ecosystem scale insights (such as optical remote sensing) to capture both community and ecosystem responses, including canopy changes that are missed with ground-based photography, to estimate multi-year C dynamics.

4.3 Limitations

However, we note that there are some uncertainties with the methods used in this study. Despite using a greenness index that is robust to differing lighting conditions (Sonnentag et al. 2018), we acknowledge that the use of different sensors used to collect photographs may impact the greenness values measured. As mentioned previously, we do not compare the absolute values of greenness among sites, rather we have focused on comparing DOY at peak greenness. Furthermore, some participants sent photos weekly across the summer, while others were sent on bi-weekly or monthly intervals. We advise researchers who wish to use this methodology in their own research to use the same sensor each time they take a photograph of their plots (see the PeatPic Protocol for more details). Last but not the least, as is the case in all studies attempting to draw general conclusions across broad regions with limited data, we acknowledge that our sites have limited coverage compared to the global distribution of northern peatlands. As such, the GLP drivers that we identified are biased to the environmental conditions found in the sites that we happened to have data from.

5. Conclusions

Our low cost and low effort smartphone photography method offers various proxies of peatland GLP, and additional future research opportunities to understand peatland phenology beyond just greening. Our study suggests that latitude, surface net solar radiation, peatland type, and vegetation type can predict leaf greening patterns across global peatlands. Green leaf phenology has implications for C fixation in peatlands and therefore could influence future peatland carbon sink capacity. These results can help us understand responses of peatland ecosystem functions to future environmental change. Lastly, better refining patterns of peatland GLP will also help refine parameters of Earth system models that currently either do not parameterize peatlands or use simplistic phenology functions taken from upland systems.

Data Availability

The data and code supporting this study will be made available via the Dryad Digital Repository: DOI: 10.5061/dryad.cz8w9gjgp. Photographs will be available on our GitHub repository.

Author contributions

SJD conceived the work. MS, EA, RA, LJA, JMB, VEJJ, MB, CB, GD-S, EdE, AH, GG, AH, S-CL, AL, MPk, MPl, JFPQ, CRP, HR, ES, A-MV and EW contributed photographs for the study. SJD, AM and VEJJ conducted the analysis. All authors contributed to the interpretation of data and writing.

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