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ORIGINAL PAPER

Volunteer-contributed observations of flowering often correlate with airborne pollen concentrations

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Abstract

Characterizing airborne pollen concentrations is crucial for supporting allergy and asthma management; however, pollen monitoring is labor intensive and, in the USA, geographically limited. The USA National Phenology Network (USA-NPN) engages thousands of volunteer observers in regularly documenting the developmental and reproductive status of plants. The reports of flower and pollen cone status contributed to the USA-NPN's platform, *Nature's Notebook*, have the potential to help address gaps in pollen monitoring by providing real-time, spatially explicit information from across the country. In this study, we assessed whether observations of flower and pollen cone status contributed to *Nature's Notebook* can serve as effective proxies for airborne pollen concentrations. We compared daily pollen concentrations from 36 National Allergy Bureau (NAB) stations in the USA with flowering and pollen cone status observations collected within 200 km of each NAB station in each year, 2009–2021, for 15 common tree taxa using Spearman's correlations. Of 350 comparisons, 58% of correlations were significant ($p < 0.05$). Comparisons could be made at the largest numbers of sites for *Acer* and *Quercus*. *Quercus* demonstrated a comparatively high proportion of tests with significant agreement (median $\rho = 0.49$). *Juglans* demonstrated the strongest overall coherence between the two datasets (median $\rho = 0.79$), though comparisons were made at only a small number of sites. For particular taxa, volunteer-contributed flowering status observations demonstrate promise to indicate seasonal patterns in airborne pollen concentrations. The quantity of observations, and therefore, their utility for supporting pollen alerts, could be substantially increased through a formal observation campaign.

Keywords Citizen science · flowering · phenology · pollen monitoring · USA National Phenology Network · *Nature's Notebook*

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Introduction

Allergic asthma and seasonal allergies are substantial human health concerns, affecting approximately 400 million people worldwide (Nur Husna et al. 2022). Symptoms associated with allergic asthma and rhinitis have significant impacts on quality of life and productivity (Melzer 2016; Melzer et al. 2009). Pollen alerts, which provide key information to those suffering from pollen-induced asthma and allergies, have the potential to reduce exposures and the resulting negative health impacts. However, creating these alerts requires spatially explicit, real-time information on pollen release.

Airborne pollen surveillance in the USA is undertaken primarily through self-funded pollen monitoring stations that are certified by the National Allergy Bureau (NAB). National Allergy Bureau pollen measurements are among the most reliable empirical source of airborne pollen concentrations in the USA, collected under the direction of an expert and meeting a suite of data quality metrics (Hall et al. 2020). Data collection frequency varies among stations; many stations collect data on weekdays during the growing season. However, station coverage is sparse across the USA, currently numbering around 80 stations, with varying lengths of data collection (Lo et al. 2019; Ziska 2020). Consequently, individuals with pollen allergies have limited data on days when they will be exposed to airborne pollen.

Various alternative information sources have been evaluated for their potential to address the large gaps in airborne pollen concentration information across the country, including Twitter posts (Gesualdo et al. 2015), Google searches (Hall et al. 2020), and over-the-counter allergy medication sales (Ito et al. 2015). Another potential source of information indicating the identity and abundance of pollen is periodic observations of phenological status. The USA National Phenology Network (USA-NPN) was established in 2007 to collect, store, and share plant and animal phenology data and information to support scientific discovery, decision-making, and an appreciation for phenology. The USA-NPN hosts *Nature's Notebook*, a rigorous platform used by thousands of professionals and volunteers to monitor the status of seasonal development and activity in plants and animals (Rosemartin et al. 2014). Since the launch of *Nature's Notebook* in 2009, over 30 million records of phenology have been contributed by both professional and volunteer scientists from thousands of locations across the USA that are increasingly used in science, management, and education applications (Crimmins et al. 2022).

Several studies have investigated whether flowering phenology can indicate pollen presence and concentration (e.g., Jato et al. 2002; Hidalgo et al. 2003; Veriankaite et al. 2010; Dabrowska 2012; Katz et al. 2019; Damialis et al. 2020). In most cases, the timing of flowering and the presence of airborne pollen correlate, though patterns vary by species. Few comparative studies have been undertaken in the USA. Further, the majority of comparative studies focus on a single location.

Observations contributed to *Nature's Notebook* indicate whether flowers or pollen cones on individual plants are open or not on a particular date. These status observations are resolved to the taxonomic level of plant species and are collected on an approximately weekly basis, though frequency varies by observer. In this study, we evaluate how well the observations of flowering phenology contributed to *Nature's Notebook* over the past 15 years match airborne pollen concentration measurements collected at nearby National Allergy Bureau (NAB) pollen counting stations over the spring season, and therefore, their utility to serve as a proxy for airborne pollen concentrations. Specifically, the aim of this paper is to explore how the strength of the relationships between the two datasets varies by plant taxa and across the USA. The foundational understanding yielded through this comparative analysis sets the stage for leveraging volunteer-contributed observations in pollen alerts and forecasts, revealing conditions under which these data are sufficient or in need of augmentation for such uses.

Methods

Flowering phenology data

The *Nature's Notebook* platform (www.naturesnotebook.org) is designed for use by professional and volunteer observers, independently or as part of an organized group (Posthumus et al. 2019; Crimmins et al. 2020). The platform consists of standardized observation protocols, a mobile app for data collection, an online interface for submitting and accessing observations, and data visualization and download tools. The USA National Phenology Network offers extensive training materials in multiple formats, sends frequent, information-rich messages to participants through email and social media, and customizes website content to feature and enhance collaborators' data collection efforts. In addition, USA-NPN staff offer ample in-person and virtual support to new and existing participants to recruit and retain participants in collecting data of the highest possible quality. Over the 14 years that *Nature's Notebook* has been in existence, over 25,000 observers have submitted observations from over 18,000 sites on thousands of plant and animal taxa.

The USA-NPN protocols embedded in *Nature's Notebook* are "status" protocols, meaning that participants are asked to report on the status of life cycle stages for an individual plant or animal species each time they make an observation and to make observations frequently over the course of the growing season (Denny et al. 2014). Each plant phenology observation is composed of "yes" or "no" responses to a series of questions pertaining to the state of a plant's leaves, flowers, and fruits. Participants select the locations where they collect observations; program guidance encourages participants to select locations that are convenient to maximize observation frequency and duration.

For this analysis, we downloaded all "status and intensity" records (Rosemartin et al. 2018; USA National Phenology Network 2022) for the "open flower" and "open pollen cones" stages in wind-pollinated tree taxa that are allergenically important and most commonly observed in *Nature's Notebook* (*Acer*, *Alnus*, *Betula*, *Carya*, *Celtis*, Cupressaceae, *Fraxinus*, *Juglans*, *Liquidambar*, Pinaceae, *Platanus*, *Populus*, *Quercus*, *Salix*, and *Ulmus*) over the years 2009 to 2021 across the conterminous USA. We removed records where multiple observers reported conflicting flowering for the same individual plant on the same day.

Next, we identified all flowering observations occurring within 50 km, 100 km, 200 km, and 300 km of each NAB station to evaluate trade-offs between flowering observation sample sizes and site heterogeneity. We determined the proportion of all records for a distinct taxon that were "yes" reports to either "open flowers" and "open pollen cones" for each day of the record. Daily measures of the proportion of individual plants with open flowers or pollen cones reported within the various buffers were smoothed with a 7-day moving average.

Pollen data

Pollen observations were provided by 47 National Allergy Bureau stations from daily volumetric measurements collected using Burkard or Rotorod samplers. To exclude zeros that would inflate correlations, we only retained observations within the 99% airborne pollen season. To define the pollen season in a way that accounts for multiple peaks within the season, we calculated the mean concentration of pollen collected on each day of the year and used a 2-week moving average to smooth the concentrations. We then defined the pollen season as the calendar days when 99% of pollen was collected.

We assigned mean annual temperatures to each NAB site and *Nature's Notebook* monitoring location using PRISM 30-year normals (1991-2020; PRISM Climate Group 2022).

Statistical analyses

We compared the 1-week moving average proportions of "open flowers" and "open pollen cones" within the buffer region with daily pollen concentrations using Spearman rank correlations. Years for which data were sparse for either airborne pollen (cumulative concentrations < 100 grains/m^3) or flowering measurements (< 10 observations of individual plant flowering status) were excluded from the analysis. In addition, to minimize the inclusion of flowering or pollen cone observations contributed from locations with conditions substantially different from that of the NAB station, observations from locations with mean annual temperatures differing from that of the NAB station by greater than 2 °C were excluded. Similarly, we only analyzed seasons where there were > 10 days where both variables were available. After applying these filters, 36 NAB stations had adequate data for one or more comparisons. We used Spearman's ρ to describe correlations for each combination of site taxon*year.

We repeated these analyses for alternate buffer region sizes surrounding NAB stations (50 km, 100 km, and 30 0km); results for these buffer region sizes appear in Fig. S1. We likewise repeated analyses using alternate temperature cut-offs (0.5, 1, 2, and 3 °C), where observations falling under each cut-off were included in the analysis. These results appear in Fig. S2. We also evaluated the effect of buffer size on the sample size of site*taxon*year comparisons (Fig. S4). To explore how buffer size affected environmental similarity between the NAB stations and corresponding *Nature's Notebook* observations, we compared how they differed in mean annual temperature (Fig. S5) in both general direction and magnitude. We then applied Games-Howell post-hoc tests to determine statistical differences among buffer sizes.

Because this study did not involve human subjects, no institutional review board approval was necessary.

Data summarization

We summarized the strength of relationships for tests undertaken by site*taxon*year. Next, to determine whether the strength of relationships between flowering status collected and pollen concentrations varied across geography, we explored relationships between latitude and Spearman's ρ and longitude and Spearman's ρ. We also compared the number of unique observers submitting reports of flowering status surrounding pollen counting stations and Spearman's ρ values between flowering observations and pollen concentrations by taxon using Spearman's correlations. Finally, we explored relationships between the number of unique dates for which the proportion of individual plants with open flowers were available within a year and Spearman's ρ by taxon.

All analyses were undertaken in R v4.1.2 using the rnpn, tidyverse, sf, and prism packages (Hart and Bell 2015; Pebesma 2018; Wickham et al. 2019; Rosemartin et al. 2022).

Results

In total, there were 1,320,617 occurrences of flower or pollen cone status reported through *Nature's Notebook* in the period of record. The number of records contributed was low in the early years of the record, with 3809 records reported in 2009 and 7253 records reported in 2010. Observing picked up markedly in later years, with 100,000 or more records contributed every year after 2015.

There were sufficient observations of pollen concentrations and flowering status observations within the USA-NPN and NAB datasets to undertake 350 unique comparisons of the two variables at the 200 km buffer size, encompassing 15 taxa and 36 NAB stations (Fig. 1). Over half of these comparisons were significant at the $p < 0.05$ level (Table 1). Results for 50 km, 100 km, and 300 km buffers appear in Table S1.

A stronger Spearma's rank correlation between flowering status and airborne pollen concentrations indicated greater coherence in the pollen concentrations and the proportion of plants exhibiting open flowers or pollen cones. One example of such strong coherence was for *Quercus* at the Armonk, NY, NAB station in 2018 (Fig. 2a). Weaker correlations emerged when the patterns in magnitude did not match as well, such as in the case of *Acer* observations collected at the Springfield, NJ, station in 2016 (Fig. 2b), where the abundance of observations of open flowers was concentrated in March, April, and May, and *Acer* pollen concentrations exhibited many peaks from March to June. In 15–20% of cases (depending on buffer region size),

Table 1 Number, strength, and proportion of significant tests ($p < 0.05$) for comparisons of flowering status observations within 200 km of the pollen counting station and pollen concentrations

Taxon	Site* year tests	Correlation (ρ) mean ± SD	Significant tests
Acer	89	0.17 ± 0.4	45 (51%)
Alnus	2	0.57 ± 0.3	1 (50%)
Betula	34	0.34 ± 0.4	19 (56%)
Carya	9	0.20 ± 0.4	4 (44%)
Celtis	2	− 0.05 ± 0.6	0 (0%)
Cupressaceae	37	0.11 ± 0.4	22 (59%)
Fraxinus	10	0.29 ± 0.4	4 (40%)
Juglans	5	0.72 ± 0.1	5 (100%)
Liquidambar	4	0.25 ± 0.6	3 (75%)
Pinaceae	27	0.45 ± 0.3	17 (63%)
Platanus	4	0.22 ± 0.3	0 (0%)
Populus	21	0.49 ± 0.3	15 (71%)
Quercus	94	0.45 ± 0.3	65 (69%)
Salix	3	0.34 ± 0.0	0 (0%)
Ulmus	9	0.18 ± 0.4	2 (22%)
Total	350		202 (58%)

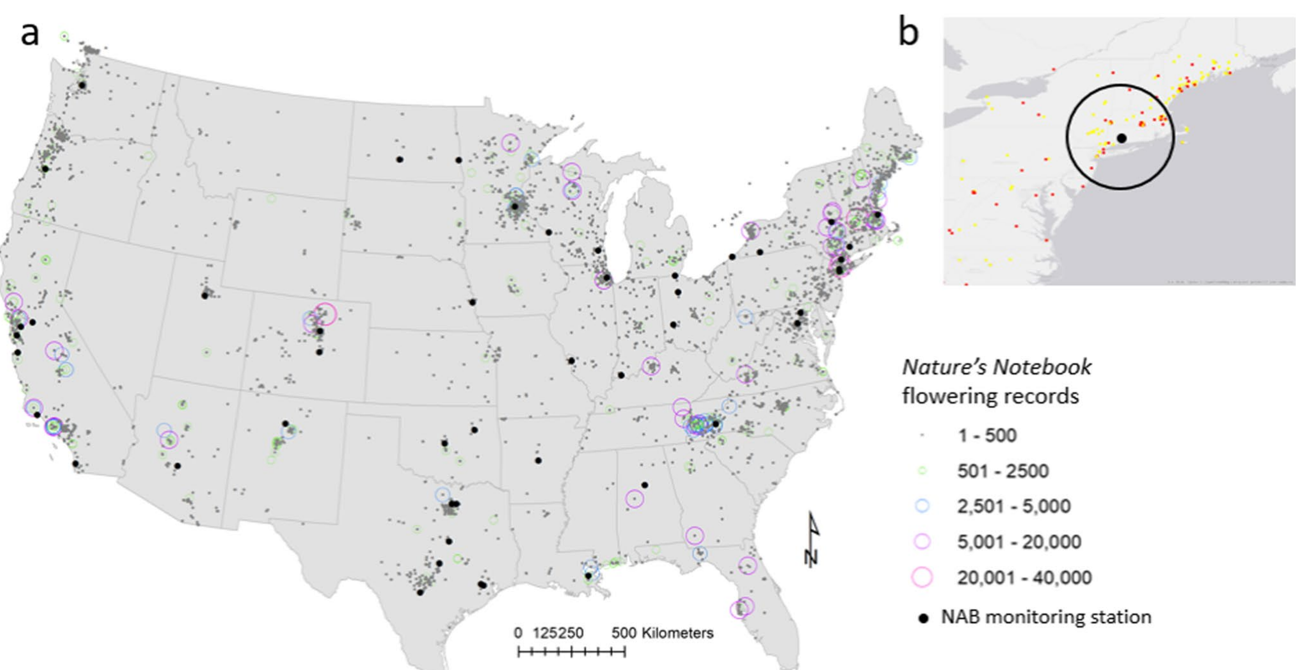

Fig. 1 **a** Flower and pollen status records contributed to *Nature's Notebook* (2009–2021) in the conterminous USA and National Allergy Bureau (NAB) certified pollen monitoring stations that provided data for this study. **b** Illustration of flowering status observations (red = open flowers; yellow = no open flowers) summarized within 200 km of a NAB pollen monitoring station on a single day

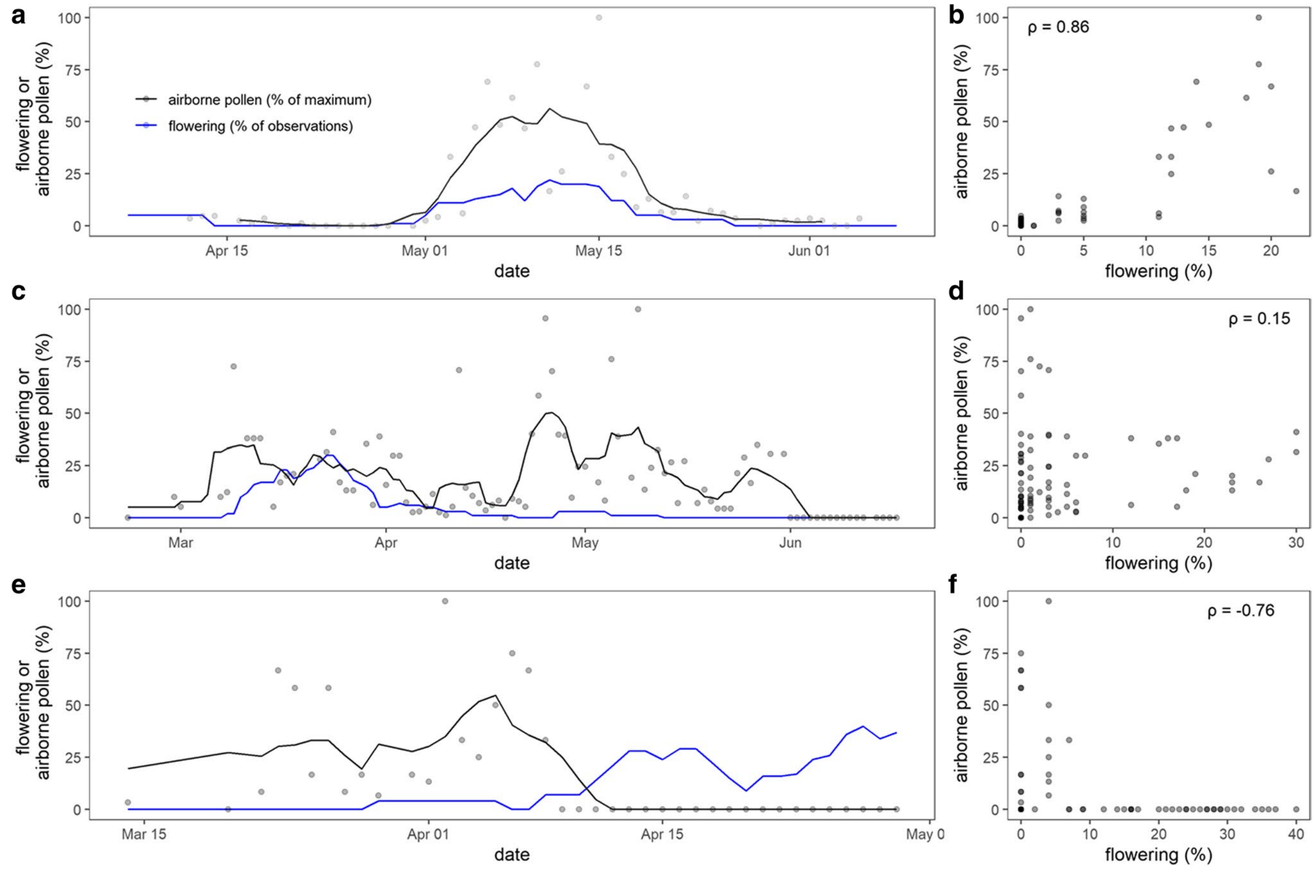

Fig. 2 Comparison of flowering status observations and airborne pollen concentrations for **a** *Quercus* within 200 km of the Armonk, NY, NAB pollen monitoring station in 2018, **c** *Acer* within 200km of the Springfield, NJ, station in 2016, and **e** *Acer* within 200 km of the Sylvania, OH pollen station in 2015. Blue lines represent the 1-week moving average of the percent of flowering status that were reported as "open" within 300 km of the NAB station; black lines represent the 1-week moving average of relative pollen concentrations; black dots are relative pollen concentrations. Scatterplots depicting the proportion of "open flowers" and daily pollen concentrations for **b** *Quercus* within 200 km of the Armonk, NY, NAB pollen monitoring station in 2018, **d** *Acer* within 200 km of the Springfield, NJ, station in 2016, and **f** *Acer* within 200 km of the Sylvania, OH, pollen station in 2015. Each point represents measurements from a single day

inverse correlations emerged (33% of which were significant), such as for *Quercus* at the Sylvania, OH, station in 2015, where pollen concentrations preceded nearly all reports of open flowers (Fig. 2c).

Relationships vary by taxa

On average, relationships between pollen concentrations and flowering observations were strongest for *Juglans* (median Spearman's $\rho = 0.79$), though the number of sites where comparisons could be made was much smaller for *Juglans* than for other taxa (Fig. 3). Correlations were comparatively high for Pinaceae (median Spearman's $\rho = 0.57$), *Populus* (median Spearman's $\rho = 0.54$), and *Quercus* (median Spearman's $\rho = 0.49$). Correlations tended to be lower for Cupressaceae (median Spearman's $\rho = 0.18$) and were especially low for *Celtis* (median Spearman's $\rho = -0.05$).

Relationships across geography

The number of comparisons that could be made was greatest in the northeastern US as well as in several cities across the country (Fig. 4). Maps depicting the number of comparisons that could be made at other buffer sizes appear in Fig. S3. There were no significant relationships between latitude or longitude and Spearman's ρ at any of the buffer region sizes.

Phenology data sampling considerations

Spearman's ρ values showed a significant relationship ($p < 0.05$) with the number of unique observers in four (27%) of 15 tests at distinct NAB stations at the 200 km buffer size, indicating that the strength of the relationship was impacted to a small extent by the number of unique *Nature's Notebook* participants contributing flowering status observations for a particular taxon within the buffer

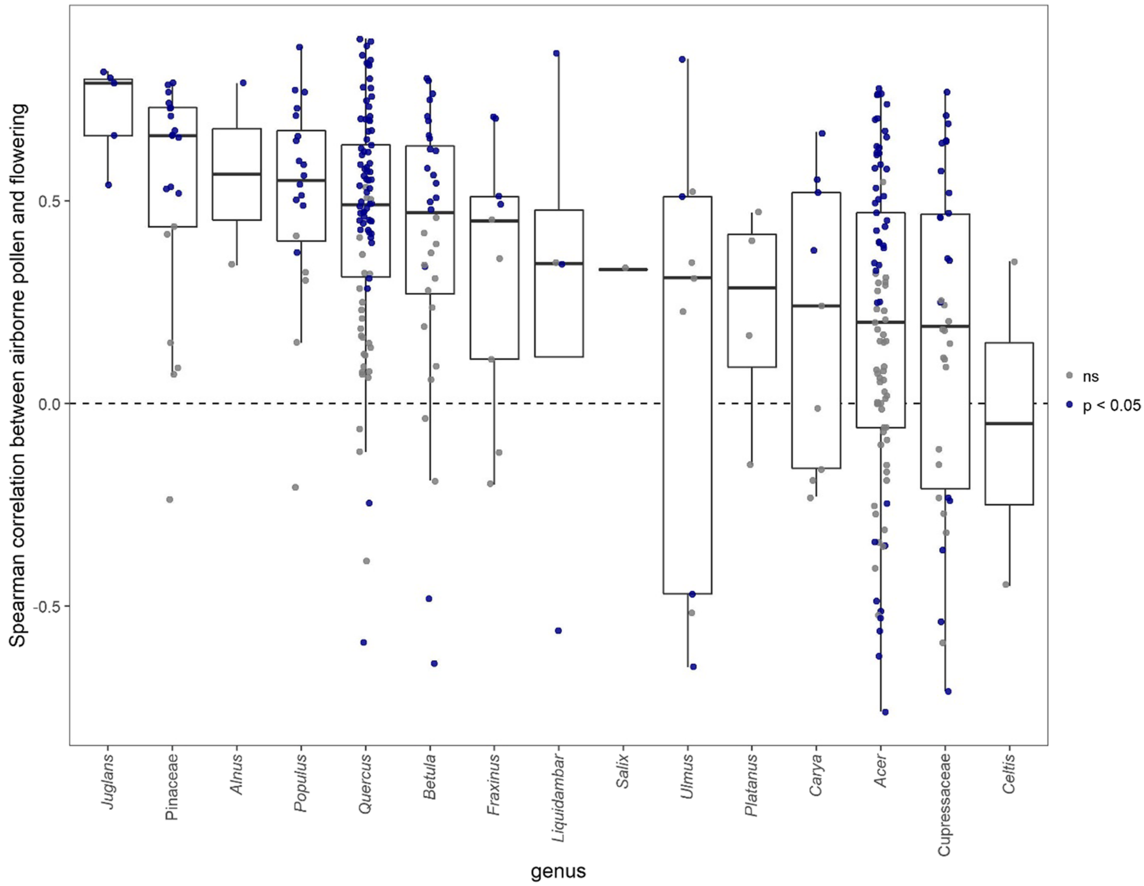

Fig. 3 Correlations between flowering and pollen cone observations collected within 200 km of a pollen counting station and airborne pollen concentrations. Each dot represents a single site × year comparison. Flowering observations originating from locations with mean annual temperatures > 2 °C from the corresponding pollen monitoring station were excluded. Boxplots and dots both reflect data points

size (Table S2). In addition, Spearman's ρ values showed a significant relationship ($p < 0.05$) with the number of observation dates in only one (7%) of 15 tests at the 200 km buffer size, indicating that relationships are generally not notably influenced by more frequent observations of flowering status over our minimum threshold of 10 observation dates in a season (Table S3).

Though increasing buffer sizes enabled more individual comparisons to be undertaken, increasing buffer sizes generally did not result in a dramatic increase in the number of flowering status observations included in comparisons (Fig. S4). Further, as buffer size increased, the mean annual temperature of *Nature's Notebook* observation locations became relatively cooler than the corresponding NAB station (Fig. S5). Similarly, as buffer size increased, the mean absolute difference in temperature between *Nature's Notebook* observation locations and the corresponding NAB station increased. In other words, changing buffer size affected both the mean and variance of the environmental similarity between the two datasets.

Discussion

The strength of relationships between flowering and pollen cone status observations and pollen concentrations evaluated in this study varied noticeably among taxa. The number of comparisons exhibiting strong relationships was relatively small. However, patterns evident in these results point to the potential to leverage freely available flowering status observations to better characterize airborne pollen at the level of a distinct taxon. Such information has the potential to enhance monitoring as well as efforts to forecast the timing and concentration of airborne pollen.

Strong correlations between phenology observations and airborne pollen concentrations indicate that monitored trees are similar to the ones whose pollen is sampled at NAB stations. In these cases, observations of flower and pollen cone status by *Nature's Notebook* participants contribute to an improved understanding of the underlying biology of allergenic pollen-producing plants. Weaker relationships between flowering and pollen cone status observations and

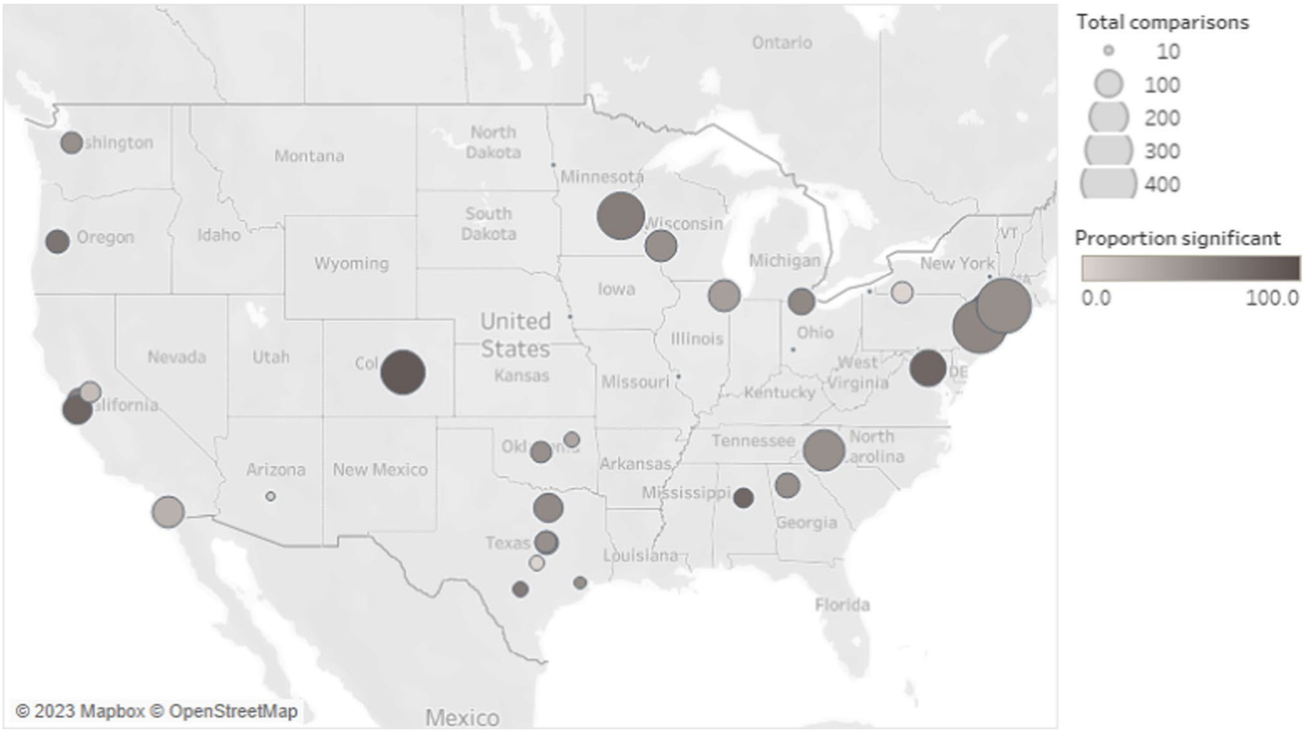

Fig. 4 Number and distribution of site × taxa × year comparisons undertaken between observations of flowering phenology collected within 200 km around NAB stations and pollen concentrations collected at the NAB stations. Size of circle reflects number of distinct taxon × year tests undertaken at the site; shade of gray reflects percent of tests that were significant ($p \leq 0.05$)

pollen concentrations observed for particular taxa presumably arise due to *Nature's Notebook* observers systematically measuring different trees than those whose pollen arrived at the corresponding NAB station. There are several plausible and non-exclusive explanations. First, there may be taxonomic differences, which can be challenging to disentangle, as NAB measurements are generally at the genus level. For example, *Nature's Notebook* observations may be concentrated on one or more species within a genus that are not the most important producers of allergenic pollen. Differences in species composition near the pollen counting station versus within the surrounding buffer could explain lower correlations, as could corresponding differences in environmental conditions. Second, long distance dispersal of pollen could play a role, as distant plants may release pollen at different times than local plants. Other possibilities include resuspension of pollen or measurement issues discussed below.

The amount of flowering status observations available for a taxon and near an NAB station is also a major factor dictating whether comparisons between flowering status and pollen count can be made. For several taxa, such as *Alnus*, *Celtis*, *Juglans*, *Liquidambar*, and *Salix*, few comparisons could be made due to insufficient dates with flowering status observations within a year. For flowering status to be of use in indicating pollen timing and concentrations for these taxa, many more observations of flowering status need to be collected. Regional variation in the amount of available *Nature's Notebook* data was substantial, suggesting that the potential benefit of phenological observations would be strongest around population centers in the northeast.

Our comparisons of flowering status observations pooled from regions surrounding pollen counting stations revealed clear tradeoffs between sample size and representativeness. As stated above, due to limited flowering status observations, summarizing flowering status observations from a larger region surrounding the NAB station enabled comparisons for more taxa to be made by increasing the number of flowering status observations available. However, larger buffers resulted in the inclusion of observations exhibiting increasingly dissimilar environmental conditions than that of the NAB station. In particular, as buffer size increased, flowering status observations reflected systematically cooler conditions than the NAB monitoring site to which they were compared. This disparity likely reflects the fact that NAB stations are frequently located in urban areas that are warmer than the surrounding region because of urban heat islands (Bornstein 1968). The timing of flowering is strongly shaped by day length and temperature in temperate ecosystems (Rathcke and Lacey 1985; Basler and Körner 2014). Accordingly, observations of flowering status originating from locations characterized by different temperature conditions than that of the NAB station are likely to exhibit differences in the timing of flowering activity. Flowering status observations pooled from a larger region may also be collected at different latitudes, elevations, or distance from the coast, all of which can influence the timing of flowering (Chmura et al. 2019).

Mismatches in the abiotic conditions occurring at an NAB station and the associated flowering status observations may explain some of the negative relationships that emerged in our results, such as *Acer* at the Sylvania, OH, station in 2015, where pollen concentrations preceded nearly all reports of open flowers (Fig. 2c). These results appear to emerge at least in part because most of the *Nature's Notebook* observations were from cooler areas (mean 0.7 °C cooler) in Michigan. Though we removed flowering status observations contributed from locations with a mean average temperature two or more degrees different from that of the NAB station to minimize the influence of observations from unrepresentative locations, additional filtering could further improve results. Such differences could also be due to mismatches in which species contributed pollen compared to which species were monitored at this station.

Data quality considerations

Because the flowering observations maintained by the USA-NPN are contributed by professionals and volunteers for reasons of their own choosing, observations are not collected following a formal spatial sampling design. Further, many participants collect observations for only one season, resulting in temporal spottiness in the data (Crimmins et al. 2022). Finally, while observations are collected approximately weekly, there are no requirements for participants to observe on a regular basis; as such, some individual plants are observed more frequently than others. We opted to summarize flowering status observations from across a buffer region and with a moving average to minimize the impacts of these potential limitations.

Volunteer-contributed flowering observations may also suffer from species misidentifications and phenophase misidentifications. The most logical misidentification for a species is a closely related species, likely in the same genus. As we pool the flowering status observations to the genus level in this analysis, observations for plants identified incorrectly at the species level but attributed to the proper genus would have no effect on our results. Observers' assessments of phenophase status may also include errors, though since these assessments are categorical in nature (yes/no/unsure), they are less likely than species identifications to be in error (McDonough MacKenzie et al. 2018). Fuccillo et al. (2015) demonstrated that, on average, participants in *Nature's Notebook* correctly assess the phenophase status of plants 91% of the time. Further, volunteers' ability to correctly assess phenophase status in flowering is typically higher than that for earlier-season phenophases such as leaf-out (Fuccillo et al. 2015).

The National Allergy Bureau pollen concentrations are collected by certified workers under the direction of a trained professional and meet data quality metrics (Hall et al. 2020). However, several limitations of these data potentially influence the relationships evaluated in this study. In particular, not all stations use the same sampling equipment, stations are sometimes relocated, samplers are located at varying heights off the ground, and station metadata documenting these potentially influential factors are limited (Hall et al. 2020; Lo et al. 2019). Further, though trained experts perform pollen counts, errors could surface from pollen grain identification and/or counts. While these limitations may affect the amount of pollen collected, they are unlikely to have strong effects on the general seasonal trends investigated here.

Finally, the simple analysis approach undertaken here may be overly conservative for estimating the relationships between the observations of flowering or pollen cone status and airborne pollen concentrations. Subsequent analyses involving more sophisticated approaches may yield stronger performance in observations contributed to *Nature's Notebook* in characterizing airborne pollen.

Opportunities

The relative abundance of flowering status records available for *Quercus*, *Acer*, and *Populus* is the direct result of coordinated efforts led by the USA-NPN to encourage data collection for these taxa. The USA-NPN's "Green Wave" campaign, which encourages observers to track phenology on *Acer*, *Quercus*, and *Populus* species, has been in existence since 2012 and has resulted in significant increases in the numbers of participants tracking phenology, individual trees under observation, and observations submitted on the taxa (Crimmins et al. 2014). Similarly, the USA-NPN has coordinated the "Pollen Trackers" campaign, focused on Ashe's juniper (*Juniperus ashei*) in Texas since 2019; since the campaign's launch, observations of juniper phenology contributed to *Nature's Notebook* have increased from a few dozen observations each year to several thousand observations of this species each year.

Leveraging the USA-NPN's demonstrated ability to mobilize data collection in support of a particular application through a *Nature's Notebook* campaign (Crimmins et al. 2014; Elmore et al. 2016; Maynard-Bean et al. 2020) could be an important next step in refining our understanding of the taxa for which airborne pollen concentrations can be predicted using observations of flowering status as well as to generate observations to support the development of process-based models and pollen forecasts. Such a campaign could focus on growing the number and frequency of observations on flowering status in close proximity to NAB stations and could be advertised to audiences with a vested interest, such as allergy and asthma patients, and through allergists' and immunologists' offices. A focused campaign has the potential to refine insights for taxa with relatively strong relationships (e.g., *Quercus* and *Juglans*) as well as to improve our understanding for taxa with limited data currently available, such as *Alnus*, *Celtis*, *Liquidambar*, and *Salix*. In addition, emphasis could be placed on particular species, such as *Acer negundo*, which produces far more pollen than other *Acer* species more commonly observed in *Nature's Notebook*. Further, the potential demonstrated in this study could be extended to additional allergenic taxa not explored here, such as grasses and ragweed. The insight that the number of individuals tracking flowering status has little impact on estimates of airborne pollen concentrations provides further support for engaging volunteers through a variety of mechanisms to generate flowering status reports.

Our findings suggest that for particular taxa, flowering status observations contributed by *Nature's Notebook* participants demonstrate promise to indicate seasonal patterns in airborne pollen concentrations. For many taxa and locations, observations must be summarized across a large region to achieve sample sizes sufficient to make comparisons. Observations collected across heterogeneous regions frequently exhibit varying conditions from that of the pollen counting station, reducing the suitability of comparisons. The quantity of flowering and pollen cone status observations—and the ability to use these observations to characterize the pollen season—could be substantially increased through a formal observation campaign. Such information could be a valuable information source to support real-time pollen alerts with local specificity.

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Declarations

Conflict of interest The authors declare no competing interests.

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