Applications
in Plant Sciences

Patterns and biases in an Arctic herbarium specimen collection: Implications for phenological research

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PREMISE OF THE STUDY: Herbarium specimens are increasingly used in phenological studies. However, natural history collections can have biases that influence the analysis of phenological events. Arctic environments, where remoteness and cold climate govern collection logistics, may give rise to unique or pronounced biases.

METHODS: We assessed the presence of biases in time, space, phenological events, collectors, taxonomy, and plant traits across Nunavut using herbarium specimens accessioned at the National Herbarium of Canada (CAN).

RESULTS: We found periods of high and low collection that corresponded to societal and institutional events; greater collection density close to common points of air and sea access; and preferences to collect plants at the flowering phase and in peak flower, and to collect particular taxa, flower colours, growth forms, and plant heights. One-quarter of collectors contributed 90% of the collection.

DISCUSSION: Collections influenced by temporal and spatial biases have the potential to misrepresent phenology across space and time, whereas those shaped by the interests of collectors or the tendency to favour particular phenological stages, taxa, and plant traits could give rise to imbalanced phenological comparisons. Underlying collection patterns may vary among regions and institutions. To guide phenological analyses, we recommend routine assessment of any herbarium data set prior to its use.

KEY WORDS   Arctic; collection biases; collection preferences; herbarium specimen; Nunavut; phenology.

Herbarium specimens are increasingly used in phenology, the study of the timing of seasonal life history events such as flowering and fruiting (Lavoie, 2013; James et al., 2018). Herbarium specimens are often collected in flower or fruit and thus provide evidence of the species' flowering or fruiting time at the specified collection location and year. Specimens have been used to correlate phenological patterns with time, geography, climate, and species' life history traits at various scales (Lavoie, 2013; Kharouba and Vellend, 2015; Panchen and Gorelick, 2017; Willis et al., 2017; Gallinat et al., 2018; Jones and Daehler, 2018). In particular, the long time series presented by herbarium collections allows the detection of the consequences of climate change (Lavoie, 2013; James et al., 2018; Jones and Daehler, 2018). However, most herbarium specimens were collected for taxonomical and biogeographical purposes, including regional, institutional, and professional contexts, without phenology in mind (Willis et al., 2017). Although field data and herbarium data have been shown to be comparable in some instances (Molnár et al., 2012; Panchen et al., 2012; Searcy, 2012; Jones and Daehler, 2018; Park and Mazer, 2018; Brenskelle et al., 2019), the phenological phase presented on a herbarium specimen occupies

an unknown position in the continuum of the phenological phase for a population-site-year combination. For example, it can be unclear whether a herbarium specimen in flower documents the start, peak, or end of flowering of that plant, and whether the specimen is representative of the population's flowering time in the year of collection (Miller-Rushing et al., 2008; Pearse et al., 2017). This can, therefore, introduce uncertainty in specimen-based estimates of a phenological event.

Arctic regions place unique limitations on the collection of herbarium specimens. The Canadian Arctic territory of Nunavut (55–83°N, 60–118°W) is 2.1 million km^2, with just 25 small communities. None are accessible by road. Sea ice restricts boat access to Nunavut to two months in late summer/early autumn. Thus, vast areas of Nunavut are difficult to access. Organised research expeditions, by boat or plane, have been the most common means of collecting herbarium specimens. The field season is constrained by a very short annual snow-free period. Together, these factors may influence collection practices and lead to biases in Arctic herbarium specimen collection in ways that affect Arctic plant phenological research.

Despite their value in global change research, herbarium collections are affected by biases related to space, time, life history traits, and taxonomy in temperate and tropical herbarium collections (Isaac and Pocock, 2015; Meyer et al., 2016; Willis et al., 2017; Daru et al., 2018; Penn et al., 2018). However, to our knowledge, collection biases have not been addressed in the Arctic. Here we define "bias" as the representation of traits among herbarium specimens that are disproportionate to their representation in nature and nonrandom collection effort over time or across species' ranges. Similar to temperate and tropical regions, the Nunavut Arctic may experience biases towards collecting at locations with easier access, such as communities, research stations, or military defense sites with airstrips or sites along the coast (i.e., spatial bias [Daru et al., 2018]). However, the very small number of easy access points in relation to the large area of Nunavut could manifest in more pronounced spatial collection patterns and biases. Thus, if herbarium specimens strongly emphasise certain locations in Nunavut, the phenology recorded on the herbarium specimens may not be representative of the phenology on a broader scale across the Territory. For example, the more accessible communities or coastal regions may experience warmer climates and/or warmer urban microhabitats that could lead to earlier phenology than more remote or inland areas (Edlund and Alt, 1989; Hertzman, 1997; Woo and Ohmura, 1997; Atkinson and Gajewski, 2002; Przybylak, 2003; Neil et al., 2010).

Temporal biases can include collecting more at certain times of the year or under certain climatic conditions (Loiselle et al., 2008; Schmidt-Lebuhn et al., 2013; Daru et al., 2018). In the Arctic, the temporal biases may be more accentuated because of the very brief Arctic growing season from mid-May to August and the severe weather conditions that may prompt most collectors to schedule expeditions in the short window of more reliable weather from late June to early August. Thus, if Arctic collectors have a preference to collect plants in flower, they may be more likely to collect specimens with atypical flowering times because of the narrow window of collection opportunity. Interannually, there is generally a tendency to collect during periods of local or world prosperity and stability (Delisle et al., 2003; Holopainen et al., 2013; Daru et al., 2018). However, increased access to Nunavut during the Cold War and during periods when Canada exerted its sovereignty presence may have resulted in different temporal patterns in high and low

collection than in non-Arctic regions. During periods when public funding is unavailable, the extremely high expense of Arctic travel in Nunavut might cause collecting to be halted or severely restricted more than in more accessible regions. The chance superposition of high or low collecting periods with climate excursions has potential to over- or under-represent climate-linked phenology trends. Such temporal bias in an Arctic collection of herbarium specimens might make it difficult to draw inferences about the phenology and climate-related phenological shifts in early- or late-season species. For example, phenological data derived from herbarium specimens collected during the typical July Nunavut field season may not capture the full extent of flowering time plasticity as it relates to interannual environmental changes, especially for species that typically start flowering before or after July.

There can also be biases in collecting efforts related to plant life history traits. Plants with more prominent flower colours or spiny stems have been shown to be over- or under-represented, respectively, in other herbarium collections (Schmidt-Lebuhn et al., 2013). Daru et al. (2018) noted a bias towards collecting shorter plants (<5 m tall) in some temperate and tropical regions, whereas Schmidt-Lebuhn et al. (2013) noted a bias against the collection of very small plants. In the Arctic tundra north of the tree line—the terrain found in all of Nunavut except the most southern border—one might expect taller plants to be most visible and therefore to be collected with disproportionate frequency. Preference for collecting certain biological taxa, often related to a biologist's specialisation or societal interest, has also been reported (Troudet et al., 2017; Daru et al., 2018). Thus, a herbarium collection may hold increased proportions of specimens related to its mandate and specifically to the specialised interests of affiliated collectors (Daru et al., 2018). Thus, certain groups of plants in the ecological community may be under- or over-represented with implications for phenological studies at plant community and landscape scales.

Given the unique spatial and temporal herbarium specimen collecting in the Arctic, we assessed the presence of spatial, temporal, collector, taxonomic, and life history trait biases in an Arctic herbarium specimen collection and discuss which of the biases and patterns found might have implication for phenological research. Specifically, we were interested in potential biases relating to the unique nature of collecting plant specimens in the Arctic and collection biases within and across phenological stages. We analysed the Nunavut Arctic herbarium specimens accessioned at the National Herbarium of Canada (CAN) to determine the following: distribution of the collection across and within years; proportion of specimens collected in relation to distance from common points of access; proportion of specimens collected at different phenological stages; proportion of specimens collected at start, peak, or end of flowering; and number of specimens collected per collector, taxonomic group, flower colour, growth habit, and plant size.

METHODS

Data set

We extracted all herbarium specimen records for Nunavut from the CAN database. The resulting 29,746 specimens represent approximately 85% of CAN's Nunavut plant collection and 643 vascular plant species (mean and range of specimens per species: 46.23 and 1–758, respectively). Currently all the accessions collected by the

current staff are databased, whereas data entry for historic specimens and specimens contributed by other collectors is still being completed. Opportunistic databasing has often proceeded systematically within the taxonomically organised CAN collection, introducing temporary taxonomic biases to the database that are distinct from the permanent taxonomic biases inherent to the collection. Although CAN holds the largest collection of Nunavut herbarium specimens, there are considerable accessions at the Agriculture and Agri-Food Canada National Collection of Vascular Plants (DAO) and smaller collections at other herbaria (Panchen and Gorelick, 2017) that remain to be databased. Consequently, we focus our study on a single herbarium.

Temporal distribution and precision

We assessed the number of herbarium specimens collected each year to determine periods of high and low collection intensity. Because phenological studies using herbarium specimens require a precise date of collection, we determined the percentage of specimens that recorded the day of collection versus those that only included month and/or year. We also investigated whether more recent specimens were more likely to record the exact date than older specimens. To determine whether there has been a trend towards collecting earlier over the years, we correlated year of collection with day of collection for all records. Given the short snow-free season in Nunavut and the May-to-August growing season, we determined the proportion of specimens collected each month and each week.

Spatial distribution

To maximise the number of specimens included in the spatial analysis, we first assessed geographic coordinates for data entry errors. In addition, because of the complexity and length of the Nunavut coastline, as well as the low precision of geographic coordinates associated with some herbarium specimens, we included a 2500-m buffer (approximately 0°1.35′ of latitude or longitude) around the current administrative boundaries of Nunavut (polygon downloaded from Natural Resources Canada at https://open.canada.ca/data/en/dataset/306e5004-534b-4110-9feb-58e3a5c3fd97). In total, there were 26,558 herbarium specimen records used in the spatial analyses (Appendix S1).

To assess the spatial patterns of collections, we calculated the density of specimens per 2500 × 2500 m pixel and the distance to the nearest community of each individual record using the R package *geosphere*. Our list of communities included year-round communities, research stations, weather stations, Canadian Forces bases, and Distance Early Warning (DEW) line sites ($n = 90$). To determine whether specimens have been randomly collected across space, we tested for spatial autocorrelation in the locations of specimens irrespective of species or the collection effort at a given site (i.e., only unique locations were considered [$n = 3767$]). To do so, we used Moran's I and tested for significance using a Monte Carlo simulation ($n = 99$ simulations, *spdep* package in R). Finally, to test for the presence of a spatial collection bias, we modeled the relationship between the density of specimens in each pixel that contained one or more specimen records and the distance of the pixel centroid to the nearest community using the *raster* package in R. Given the nonlinearity of the relationship, we fit a log-linear model. All spatial analyses were performed using R version 3.3.2 (R Core Team, 2016).

Phenology

To determine the percentage of specimens collected at various phenological phases, we assigned all herbarium specimens of 29 species (Table 1) to one of eight phenological categories: in (flower) bud; in flower; in fruit; dispersing seed; in flower and fruit; with vegetative propagules; without flowers, fruits, or vegetative propagules; and senesced prior to collection. In the rare case (less than once or twice per species except for species with a raceme or similar) where there were flower buds and flowers, we scored the specimen as "in flower." The majority of Arctic species pre-form their flower buds the year before flowering and the buds overwinter underground (Sørensen, 1941).

To determine whether herbarium specimens collected in flower are typically collected at start, peak, or end of flowering, we inspected all herbarium specimens in flower for 11 of the above-mentioned species (Table 1). These species were selected for having inflorescences in the form of a spike, raceme, or similar flowering structure with flowers opening sequentially along a flower stem, making the start, peak, or end of flowering discernible in preserved specimens. We classified each specimen according to flowering stage: at the start of flowering with flowers open only at the base of the spike or raceme; at peak flower with flowers open in the middle of the spike or raceme; or at the end of flowering with flowers only open at the top of the spike or raceme. All other flowers above or below the open flowers were in bud or the petals had wilted or dropped.

To determine whether the flowering times as indicated by herbarium specimens reflected the flowering times documented in the field, we subjected data for 28 of the above species (Table 1) to Wilcoxon signed-rank tests comparing the mean day of year (DOY) for specimens in flower across all years of collection with the mean DOY of peak flowering of approximately 30 randomly tagged plants of each species at sites at Iqaluit, Baffin Island (64°N), and Lake Hazen, Ellesmere Island (82°N), Nunavut, Canada in 2014 (for survey details see Panchen and Gorelick, 2016). Iqaluit is a coastal location with relatively easy access, while Lake Hazen is a very remote inland location that is much more difficult to access. The tagged plants were monitored throughout the 2014 growing season and peak flower determined through flower counts. The 2014 monthly temperatures during the growing season (May–August) in Nunavut were similar to the 1981–2010 long-term average (Panchen, 2016), thus minimising any differences in the comparison caused by interannual differences in climatic conditions.

Collectors

We calculated the number of herbarium specimens contributed by each collector. Where a specimen label listed more than one collector name, we used the first name listed (primary collector). We identified the collectors who cumulatively collected 90% of the Nunavut CAN specimens (top collectors) by sorting the primary collectors by number of specimens collected. We calculated the percentage of collectors these top collectors represented. To determine whether the number of specimens collected per collector per year is increasing over time, we correlated top collectors' mean number of specimens contributed per year with collectors' mean year of collecting over their collecting career (Appendix S2). We determined the mean DOY of collection for each of the top collectors and ran a Shapiro–Wilk test for normality of the collection date by the top collectors.

TABLE 1. Species for which herbarium specimens were inspected to assess phenological phase and flowering stage.

Species	N	Flower stage[a]	Mean flower DOY[b]	SD flower DOY[b]	No. flower DOY[c]	Iqaluit flower DOY[d]	Lake Hazen flower DOY[d]
Androsace septentrionalis L.	82		188	11.25	27		175
Arnica angustifolia Vahl	99		206	15.53	70	193	193
Astragalus alpinus L.	135	Y	202	15.40	93	199	
Cardamine pratensis L.	68	Y	217	11.85	53	218	
Chamerion latifolium (L.) Holub	160		205	12.52	94	212	194
Diapensia lapponica L.	75		194	12.99	29	188	
Dryas integrifolia Vahl	250		198	15.01	148	188	177
Erigeron compositus Pursh	37		194	14.70	27		182
Erysimum pallasii (Pursh) Fernald	67	Y	185	13.81	23		173
Eutrema edwardsii R. Br.	98		197	14.79	43	174	182
Oxytropis maydelliana Trautv.	145	Y	211	16.97	108	198	
Pedicularis arctica R. Br.	77	Y	199	14.95	64		181
Pedicularis capitata Adams	112		203	11.22	67		187
Pedicularis flammea L.	67	Y	199	12.45	35	185	
Pedicularis hirsuta L.	163	Y	200	13.92	104	181	177
Pedicularis lanata Willd. ex Cham. & Schltdl.	101	Y	193	15.23	66		
Pedicularis lapponica L.	62		202	14.46	48	186	
Pyrola grandiflora Radius	114	Y	212	17.33	71	206	
Ranunculus nivalis L.	98		199	20.99	60	167	
Ranunculus sulphureus Sol.	119		200	15.31	77		182
Rhododendron tomentosum Harmaja	119	Y	202	16.70	72	199	
Saxifraga aizoides L.	79		213	13.02	51	216	
Saxifraga cernua L.	243		211	14.70	164	194	
Saxifraga cespitosa L.	302		206	16.47	229	196	198
Saxifraga flagellaris Willd.	83	Y	205	15.68	68		190
Saxifraga hirculus L.	180		212	14.76	139		192
Saxifraga oppositifolia L.	240		190	17.99	131	166	171
Saxifraga tricuspidata Rottb.	202		207	15.00	133	203	197
Tofieldia pusilla (Michx.) Pers.	99		203	10.83	45	197	

Note: DOY = day of year; *N* = number of herbarium specimens inspected.
[a]Species whose herbarium specimens were assessed for flowering stage.
[b]Mean and standard deviation of the DOY of those herbarium specimens collected in flower.
[c]Number of flowering specimens inspected.
[d]Mean peak flowering DOY of plants observed in flower at Iqaluit, Baffin Island, and Lake Hazen, Ellesmere Island, Nunavut, Canada, in 2014 (Panchen and Gorelick, 2016).

Plant traits

We categorised each herbarium record according to each of the following criteria: taxonomic family, flower colour (green, pink, purple, purple-yellow, white, white-yellow, and yellow), growth habit (annual, bulb, aquatic, clubmoss, deciduous shrub, evergreen shrub, fern, forb, grass, horsetail, rush, and sedge), and plant height in 5-cm increments (<5 cm, 5–9.9 cm, etc. to ≥100 cm). The family was obtained from the CAN database, where the taxonomy largely follows the Database of the Vascular Plants of Canada (VASCAN) (Brouillet et al., 2010). Flower colour, growth habit, and plant height were obtained primarily from Aiken et al. (2011) and from Porsild and Cody (1980) when the species was not described in the former. These florae describe a height range for each species. Thus, we assigned each specimen of a species the midpoint of the height range described in the applicable flora. For flower colour, we obtained data for 320 species and 15,679 herbarium specimen records; for growth form, 608 species and 29,569 records; and for plant height, 312 species and 18,271 records. Graminoids were not categorised for flower colour or plant height. We determined the number of specimens collected for each family, flower colour, growth form, and plant height group (Appendix S3). In the absence of bias, we would expect the number of herbarium specimens per flower colour, growth form, and plant height to be proportional to the number of species in the florae for each flower colour, growth form, and

plant height. Thus, we ran chi-squared tests to determine if there was a difference between the actual number of herbarium specimens collected per flower colour, growth form, or plant height in the CAN collection and the expected number (Appendix S3).

RESULTS

Temporal distribution and precision

Herbarium specimens in the CAN data set were collected as early as 1847 and are databased up to 2015. The day, month, or year of collection was recorded on 97.1% of specimens (28,874 records). Of the specimens with no exact date (872 records), 51.8% recorded the month and year, 36.7% recorded only the year, and 11.5% did not record day, month, or year. There were 36.9% of specimens collected before 1900 that did not include the full day, month, and year information, compared with 6% of specimens collected 1900–1949 and only 1.5% of specimens collected 1950–1999. There was a statistically significant but extremely weak trend towards collecting earlier in the year from 1847 to 2015 ($R^2 = 0.07$, $P < 0.0001$, $N = 28,427$) (Appendix S4).

There was evidence of inter-annual temporal bias (Fig. 1). Periods of high collection occurred in the 1920s, 1950s, 1960s, and 2010s, while periods of low collection occurred prior to the 1920s
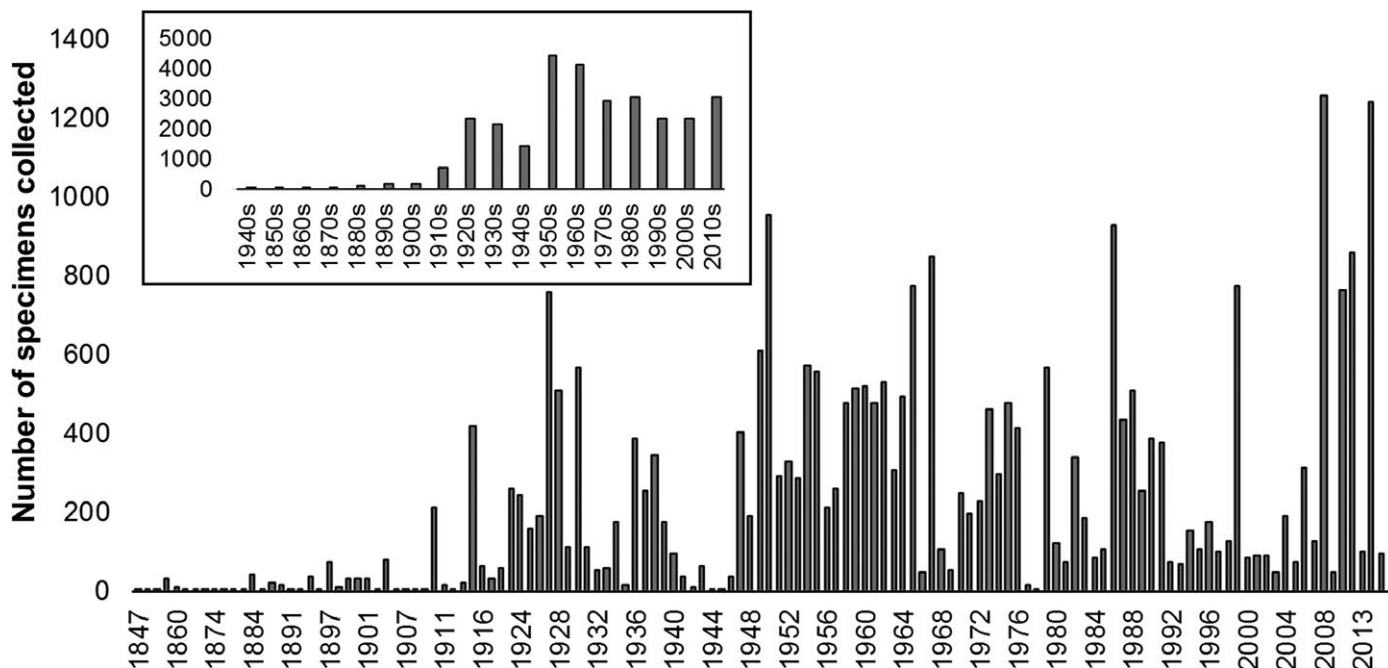
FIGURE 1. Number of Arctic herbarium specimens collected each year (1847–2015) and each decade (inset) in Nunavut, Canada, and accessioned at the National Herbarium of Canada (CAN).

and during the 1940s. Collecting during the 1930s, 1980s, and 1990s was sporadic. There was also evidence of intra-annual temporal bias (Fig. 2). More than half (52.2%) of the specimens were collected in July and more than one-third (38.3%) were collected in August. Small proportions were collected in June and September (5.8% and 3.4%, respectively), and collecting in the remaining months (October to May) was negligible (less than 0.3% combined) (Fig. 2A). The greatest number of specimens were collected in the last week of July (14.5%), and 95% of collecting occurred between the last week of June and first week of September (Fig. 2B).

Spatial distribution

There has been very sparse sampling across Nunavut. Only 0.63% of the 2500 × 2500 m pixels that make up Nunavut contained one or more herbarium specimens (total number of pixels in Nunavut = 370,151). Among the pixels that contained specimens, 31% had only a single specimen. The highest density of records was around Iqaluit, the capital of Nunavut (Fig. 3). High densities of records were also found around Eureka (a weather station, Canadian Forces base, and research station) and around the year-round communities of Cambridge Bay, Coral Harbour, Kugluktuk, Rankin Inlet, Resolute Bay, and Sanikiluaq. The specimens were not randomly distributed across space (Moran's I = 0.68, P = 0.01).

There was evidence of a spatial bias in the collection. Areas with higher densities of specimens were closer to communities (Fig. 4; R^2_{adj} = 0.01, P < 0.001). The median distance between individual records and the nearest community was 27 km (SD = 82 km). Eighteen percent of all records (4806 records) were found 2500 m from the coast, and 21% of all records (5766 records) were found 5 km from the coast.

Phenology

There was evidence of a preference to collect specimens in the flowering phase and in peak flower (Fig. 5). More than two-thirds (67.1%) of the herbarium specimens of the 29 species assessed for phenological phase (Table 1) were collected in flower, 16.1% were collected with fruits, 6.3% were dispersing seed, and 6.1% were collected without flowers, fruits, or vegetative propagules (Fig. 5A). Given that plants of these 29 species are in flower for approximately one week to one month, depending on the species (Panchen and Gorelick, 2016), and the growing season is approximately three months, we would have expected one-third or fewer of plants to be collected in flower if collection of plants was distributed evenly across the growing season. More than two-thirds (68.8%) of the herbarium specimens of the 11 species assessed for flowering stage (Table 1) were collected at peak flower, whereas 9.9% were collected at start of flowering and 21.3% at end of flowering (Fig. 5B). If the opening of flowers progresses uniformly along an inflorescence, we would have expected one-third of flowering specimens to be in each of start, peak, and end of flowering.

There was evidence of a bias in flowering time in the specimens. There was a significantly later date of flowering recorded on herbarium specimens than was observed in the field in 2014 at Iqaluit (P = 0.0002, 10 days later) and Lake Hazen (P < 0.0001, 15 days later). It should be noted that conspecifics at Lake Hazen were found to flower significantly earlier at Lake Hazen than at Iqaluit even though Lake Hazen is approximately 18° latitude farther north (Panchen and Gorelick, 2016); this may help to explain why the difference between herbarium- and field-based flowering times is greater for Lake Hazen in this analysis.
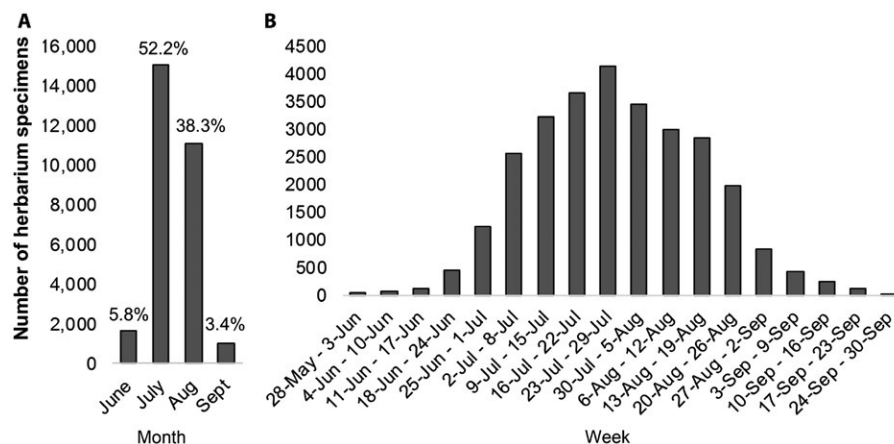
FIGURE 2. Number of herbarium specimens collected between June and September (A) and between Week 22 (28 May to 3 June) and Week 40 (1–7 October) (B) in Nunavut, Canada, and accessioned at the National Herbarium of Canada (CAN).

are under-represented in the collection. The number of herbarium specimens collected per height group differed significantly from the expected number (χ^2 = 3394.68, df = 17, P < 0.0001). Species of heights <5–20 cm and 65–75 cm are over-represented in the collection (Fig. 7C, Appendix S3). Plants 5–20 cm are much more over-represented than very small plants (<5 cm tall) (Appendix S5). The 65–75-cm categories account for just three species (*Hippuris vulgaris* L., *Salix calcicola* Fernald & Wiegand, and *S. glauca* L.) (Fig. 7C, Appendix S3). However, 92% of specimens collected were less than 25 cm and the height distribution profile, without adjusting for the number of species per height category, is reflective of the distribution of plants' heights in Nunavut (Appendix S5).

Collectors

Of the 371 unique primary collectors, 88 (23.7%) collected 90% of the Nunavut herbarium specimens at CAN (Appendix S2). Among these top 88 collectors, there was a significant trend towards collecting more specimens per year in more recent years (R^2 = 0.13, P = 0.0005, N = 88). The top 88 collectors contributed an average of 93 herbarium specimens/year, in an average of four collecting years over an average of 12 years. We found that the collection date by the top collectors was not normally distributed (W = 0.94, P = 0.0004), suggesting that there are temporal biases among collectors as to when they collect herbarium specimens.

Plant traits

The most collected families were Poaceae and Cyperaceae (Fig. 6). The most common wind-pollinated families (Poaceae, Cyperaceae, Salicaceae, Juncaceae) are among the top 10 families collected, and constitute 42% of all specimens collected. Among the top 20 collected families, Poaceae, Brassicaceae, Saxifragaceae, Caryophyllaceae, Salicaceae, Orobanchaceae, Papaveraceae, Equisetaceae, Plumbaginaceae, and Tolfieldiaceae are over-represented in the collection when compared to the expected number of specimens based on the number of species per family present in the documented Nunavut florae.

There was evidence of plant trait bias in the collection (Fig. 7). The number of herbarium specimens collected per flower colour differed significantly from the number expected based on the colours represented among species in the documented florae (χ^2 = 816.11, df = 6, P < 0.0001). Species with white flowers or flower heads with white ray flowers and yellow disc flowers are over-represented in the collection, while all other flower colours are under-represented (Fig. 7A, Appendix S3). The number of herbarium specimens collected per growth form differed significantly from the expected number (χ^2 = 2689.41, df = 11, P < 0.0001). Grasses, horsetails, rushes, sedges, forbs, and deciduous shrubs are over-represented in the collection (Fig. 7B, Appendix S3). Annuals, aquatics, bulbs, clubmosses, evergreen shrubs, and ferns

DISCUSSION

In this study, we found evidence of collection biases in a major Arctic herbarium collection. Specifically, we detected patterns and biases across time, space, phenological phases, taxonomy, and life history traits; some of these patterns and biases have implications for phenological studies.

Collection patterns and biases with implications for phenological studies

There was an intra-annual temporal bias where the majority of herbarium specimens were collected in July, even though plants are in flower in Nunavut from May until August (Aiken et al., 2011; Panchen and Gorelick, 2016). This intra-annual temporal bias combined with the bias to collect plants in peak flower suggests that flowering herbarium specimens of early-spring-flowering species, such as the purple saxifrage (*Saxifraga oppositifolia* L.) (Panchen and Gorelick, 2016), or late-summer-flowering species, such as alpine bistort (*Bistorta vivipara* (L.) Delarbre), may be atypical plant specimens that flowered later or earlier in the year, respectively, than the co-existing plants in their populations. However, if the same bias persists over the entire collection period, the data could still be used to evaluate shifts in phenology over time. On the other hand, if the collection bias is only present in some areas or time periods, then phenology shifts found in an analysis of the data could be driven by this collection bias.

We found that collectors preferentially collect plants in flower, more specifically, in the peak flower stage. Of the 29 species assessed for phenological stage, two-thirds were collected in flower, and of the 11 species assessed for individual flowering stage, two-thirds were collected in peak flower, when we would have expected one-third to be collected in flower and one-third of flowering specimens to be collected in peak flower. This suggests a bias by collectors towards collecting plants that are in peak flower regardless of the flowering time of the population or location. We found that the mean herbarium specimen flowering date was significantly later than field observations. This maybe the result of Arctic collectors

capturing late-flowering individuals of populations for which peak flowering occurred earlier in the growing season given that the majority of collections are made later in the growing season (Fig. 2). Even though 2014 summer temperatures were similar to the long-term average, the difference could also be an artifact of comparing a single year's observed flowering times at two locations with flowering times from specimens collected over multiple years and multiple locations where microclimates and climatic conditions could differ from those of 2014.

We found that collection effort increased closer to major points of access. This spatial bias may lead to inaccuracies in estimates of phenology through space when using herbarium specimens. For example, with the higher density of herbarium specimens collected from the more moderate coastal climate as compared with the low density of collecting in the more extreme climates inland (Edlund and Alt, 1989; Hertzman, 1997; Woo and Ohmura, 1997; Atkinson and Gajewski, 2002; Przybylak, 2003), we may wrongly conclude that plants across Nunavut have earlier and longer flowering times than they generally do. In addition, analysis of Arctic flowering time responses to temperature could be compounded by the fact that the only weather stations in Nunavut are in the same accessible areas that we suggest may be warmer than the Nunavut average (Atkinson and Gajewski, 2002; Environment Canada, 2017; Panchen and Gorelick, 2017).

Even after accounting for the number of species with certain flower colours, growth forms, or plant heights, some traits are over- and under-represented in the Arctic herbarium collection we studied. For example, we found species with white flowers, a graminoid growth habit, or taller individuals (i.e., 65–75 cm height range) are over-represented in the collection. Such biases could have implications for phenological studies of plant communities in the situation where the phenology of some species in the plant community is more accurately understood than others, due to abundant and limited herbarium specimen sample sizes, respectively. A number of non-collector bias reasons for the over and under collection by plant traits are also possible, including (a) species abundance (Daru et al., 2018); (b) duration of flowering, for example, white-flowered plants were collected the most and Arctic white heather (*Cassiope tetragona* (L.) D. Don) flowers for a relatively long time (Panchen and Gorelick, 2016); and (c) collector specialisation, which may result in some species being collected in high quantities that are disproportionate to the low number of species in that category (e.g., *Salix calcicola* and *S. glauca* in the 65–75-cm plant height categories).

Almost all specimens collected since the 1950s the specific date collected, whereas more than one-third collected before 1900 did not. Thus, our knowledge of Arctic plant phenology in the 19th
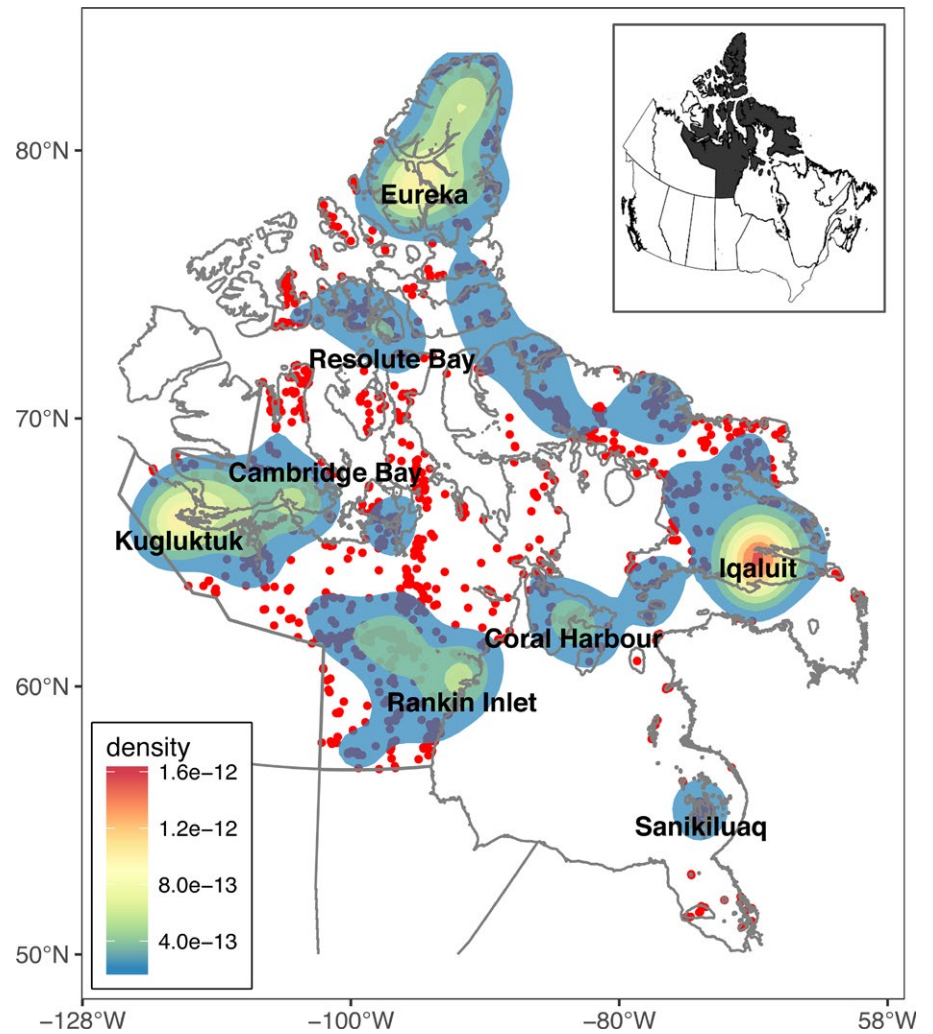

FIGURE 3. A heat map of the herbarium specimens collected across Nunavut (*n* = 26,558). To help with visual presentation, some records are hidden (see Appendix S1 for all record locations). Communities near higher record densities are labeled. Inset: map of Canada with Territory of Nunavut highlighted in black.

century is limited both by the lower number of collections and by the lower rate at which the specific date of collection was recorded. In addition, the limited sample sizes for Arctic leaf and fruit phenology introduces challenges for studying phenological phases other than flowering (Gallinat et al., 2015; Panchen and Gorelick, 2017).

The inter-annual temporal variation in collection effort that we found in this study was influenced by societal or institutional factors (see below for details) and has the potential to affect the findings of studies on the relationship between phenology and climate. For example, the 1960s, a documented cooling period in the Canadian Arctic climate (AMAP, 2012), saw continuous high collection of Nunavut herbarium specimens. Thus, including Arctic herbarium specimens from the 1960s in a time series could result in greater or smaller phenological or climate trends than an analysis that does not include the 1960s (Baker et al., 2016). For example, an analysis from the 1960s to the present would indicate greater climate change and greater phenological shifts than a study from the 1970s to the present. Subsampling or relative sample size weighting techniques could help mitigate inter-annual temporal collection biases.
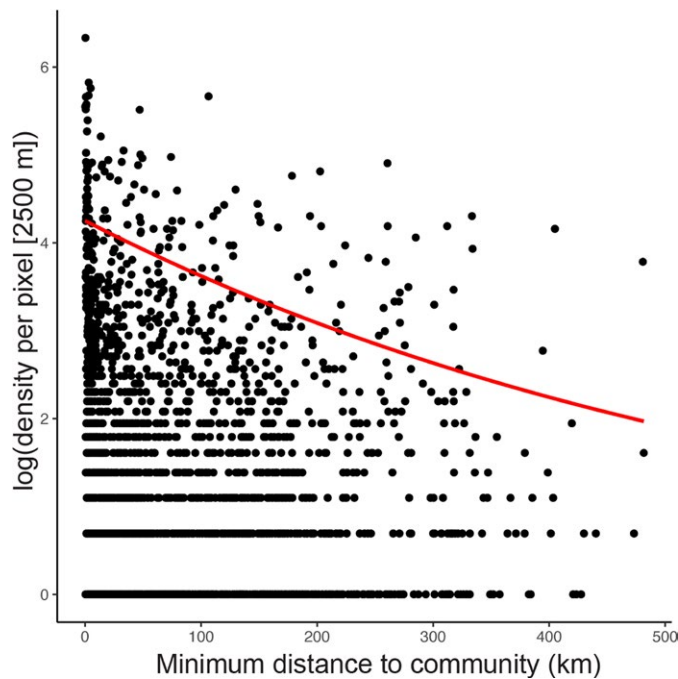
FIGURE 4. Relationship between herbarium specimen density per 2500 × 2500 m pixel and distance from nearest community. Our list of communities included year-round communities, research stations, weather stations, Canadian Forces bases, and Distance Early Warning (DEW) line sites (*n* = 90).

A large proportion (42%) of the herbarium specimens in this study represent wind-pollinated families (Poaceae, Cyperaceae, Juncaceae, and Salicaceae). Wind-pollinated species are not often collected in anthesis, and their reproductive phenological state is more challenging to determine than that of insect-pollinated species (Munson and Long, 2017; Primack and Gallinat, 2017; Panchen and Johnston, 2018). Therefore, almost half of the collection is not particularly well-suited for reproductive phenological studies because of the challenges of determining the reproductive phenological status of herbarium specimens of wind-pollinated species. Thus, our understanding of wind-pollinated reproductive phenology and how it has changed with climate change is constrained by this limitation.

Additional patterns and biases

There has been considerable variation in the annual number of herbarium specimens collected in Nunavut over the past 170 years. Some of these variations coincided with well-known political events, such as wars and sovereignty activities (Holopainen et al., 2013; Penn et al., 2018). Collecting was low during the Second World War (1930s and 1940s), but high during the Cold War (1950s and 1960s), when Canadian sovereignty concerns and early warning defense systems (DEW line) increased human activity in Nunavut. Extensive collections made by A. E. Porsild, starting in the late 1920s, marked the beginning of a focus on Arctic botanical research that contrasted with the earlier custom of incidentally collecting natural history specimens on expeditions spurred by Arctic exploration (Dathan, 2012). The 1980s and 1990s saw sporadic and decreased collection coinciding with moves towards
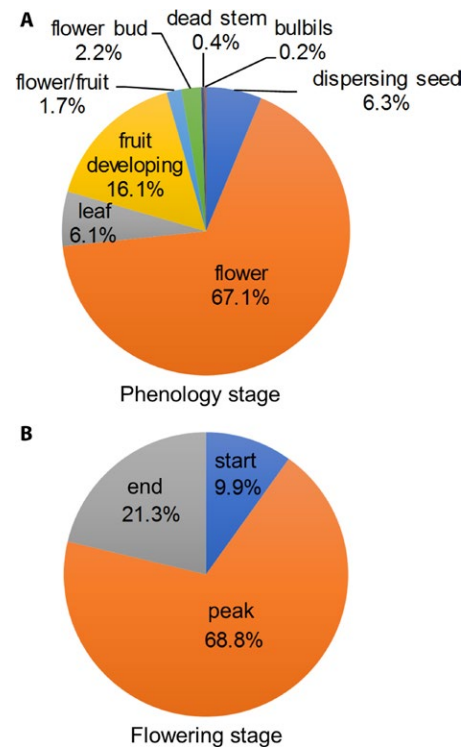

FIGURE 5. Proportion of herbarium specimens collected in each phenological phase for 29 species (Table 1) (A), and start, peak, or end of flowering for 11 species (Table 1) (B). If collection of plants was distributed evenly across the growing season and flowering progresses uniformly along an inflorescence, we would have expected approximately one-third or fewer of plants to be collected in flower and one-third of flowering plants to be collected in each of start, peak, and end of flowering, respectively. flower bud = specimens with flower buds; flower = specimens with flowers; fruit = specimens with fruit; dispersing seed = specimens dispersing seed; flower/fruit = specimens with flowers and fruits; bulbils = specimens with vegetative propagules; leaf = specimens without flowers, fruits, or vegetative propagules; dead stem = specimens that senesced prior to collection.

molecular studies. Major administrative and physical restructuring of the Canadian Museum of Nature in the 1990s likely also reduced field trips. The 2010s have seen a resurgence in collecting with the Canadian Museum of Nature's renewed strong Arctic focus, including projects to document Canadian Arctic plant distributions and the hiring of new research and collections staff in the late 2000s. We recommend that when a data set is drawn from a single institutional source, it may be useful to consider institutional history, and in general we recommend understanding the history of the time period from which the collection is drawn. This will become more important as increasingly aggregate data sets from multiple institutions are employed where the researcher will be much less familiar with the biases and preferences of individual institutions and collectors.

Botanical collections often exhibit the Pareto distribution, where a small subset of the collectors (10%) account for the majority of specimens (90%) (Isaac and Pocock, 2015; Daru et al., 2018). Analysis of a biological collection therefore risks influence by bias associated with the collection styles of the top collectors.

In the Nunavut CAN collection, just under a quarter of the collectors contributed 90% of the herbarium specimens (90 : 24 ratio). Thus, the risk of collector bias in this Arctic specimen collection would appear to be less than for a typical herbarium. However, taxonomically, graminoids and willows (*Salix* L. sp.) were represented in greater numbers than were expected, reflecting some of the specialisation of botanists at the Canadian Museum of Nature. The effect of these research interests is compounded by the fact that the collections of current and recent research scientists tend to be databased, whereas those of past collectors make up the bulk of legacy databasing projects, which are undertaken opportunistically, over time, and are ongoing in many herbaria. As it becomes possible to incorporate more data sources, thus aggregating herbarium specimen data across herbariums through online tools such as Canadensys (VASCAN; http://www.canadensys.net), the Global Biodiversity Information Facility (GBIF; https://www.gbif.org), iDigBio (https://www.idigbio.org), and Symbiota (http://www.symbiota.org), the influence of institutional collecting biases such as staff specialisations will decrease. However, until these databases represent 100% of the collections, researchers should be cognisant of the potential biases in the specimen data available online.

Challenges related to Arctic travel such as emphasis on July collecting, lower number of institutions and individuals participating in Arctic field work, fewer collections possible per unit effort/investment, and low density of collections across a large geographical area, may accentuate or create different biases than those found in tropical and temperate natural history collections.

We found a large over-collection of the grasses (Poaceae) and a large under-collection of Asteraceae. Taxonomic biases in biological collections are acknowledged (Troudet et al., 2017). At CAN, graminoids are among the most taxonomically and systematically studied families, which may help to explain the over-collection of Poaceae and Cyperaceae. In addition, these two families are dominant in the Nunavut Arctic landscape. Daru et al. (2018) also found preferential collection of graminoids in Australia and South Africa, suggesting that taxonomic collection biases for some families in the Arctic match those of some temperate and tropical regions. The under-collection of Asteraceae in the Arctic, however, contrasts with temperate and tropical collections where it has been shown to be one of the most over-collected families. Many Asteraceae species are late-season flowering and also show dramatic inter-annual differences in flower abundance (Panchen, 2016), which may partially explain the under-collection because they are less likely to be in flower, and thus collected, during the July field season. Only 80% of the Asteraceae specimens covering 75% of Asteraceae species in the collection have been databased. However, the incomplete databasing still does not explain why the actual number of Asteraceae specimens in the collection is only 50% of the expected number. This again highlights the importance for users of herbarium collection databases to be
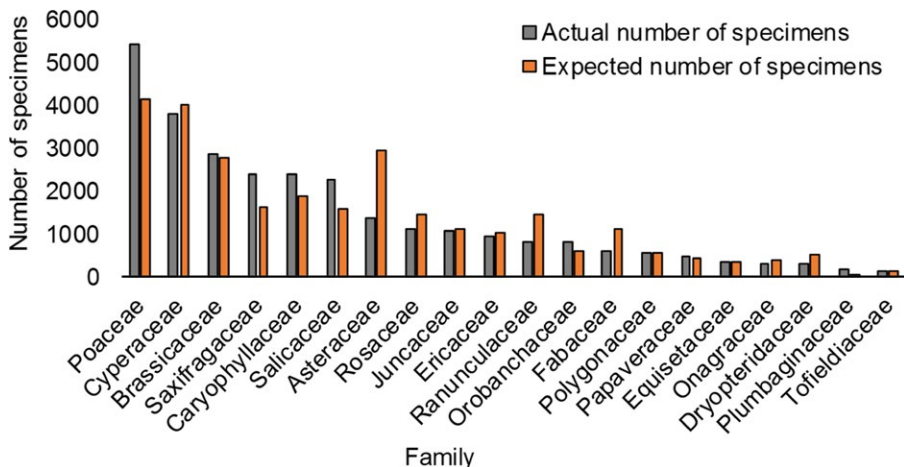

FIGURE 6. Actual and expected number of specimens for the top 20 collected plant families in Nunavut, Canada, and accessioned at the National Herbarium of Canada (CAN).

cognisant of potentially incomplete data sets derived from online tools.

Opportunities

Our results for an Arctic herbarium specimen collection are consistent with other papers on temperate collections showing that herbarium specimens can be a substantial source of phenological data (Willis et al., 2017; James et al., 2018). More than 97% of the records in this study included a specific date of collection, indicating that herbarium specimens can be used to study plant phenology in the Arctic. Although the extremely weak negative relationship between day of collection and year of collection (Appendix S4) could indicate a trend towards earlier collecting in more recent years, we suggest that the trend is negligible and may be an artifact of a preference to collect herbarium specimens in flower, in conjunction with climate-linked trends towards earlier flowering times (Høye et al., 2007; Cadieux et al., 2008; Ellebjerg et al., 2008; Barrett et al., 2015; Panchen and Gorelick, 2017).

The high proportion of flowering specimens provides a great opportunity for Arctic flowering phenological studies. Given the rapidly changing Arctic climate (AMAP, 2012; Stocker et al., 2013), there is potential to use Arctic herbarium specimens to address questions on the flowering-time responses of Arctic plants to climate change and relate these responses to evolutionary and life history trait patterns (Molau et al., 2005; Davies et al., 2013; Mazer et al., 2013; Panchen and Gorelick, 2017; Park et al., 2019). However, given the significant difference we found in mean flowering times of herbarium- versus field-based observations, increased caution may be required for Arctic environments. Using species with short flowering durations in herbarium-based phenological studies could help mitigate the bias to collect plants in peak flower, as the opportunity to collect early- or late-flowering individuals is reduced (Panchen et al., 2012; Panchen and Gorelick, 2017). Alternatively, counting or estimating the proportion of reproductive units in each stage on a herbarium specimen or using finer-scale stages (Calinger et al., 2013; Ellwood et al., 2019; Pearson, 2019) rather than using broader categories such as "flowering" or "in fruit" could also help mitigate this bias. In
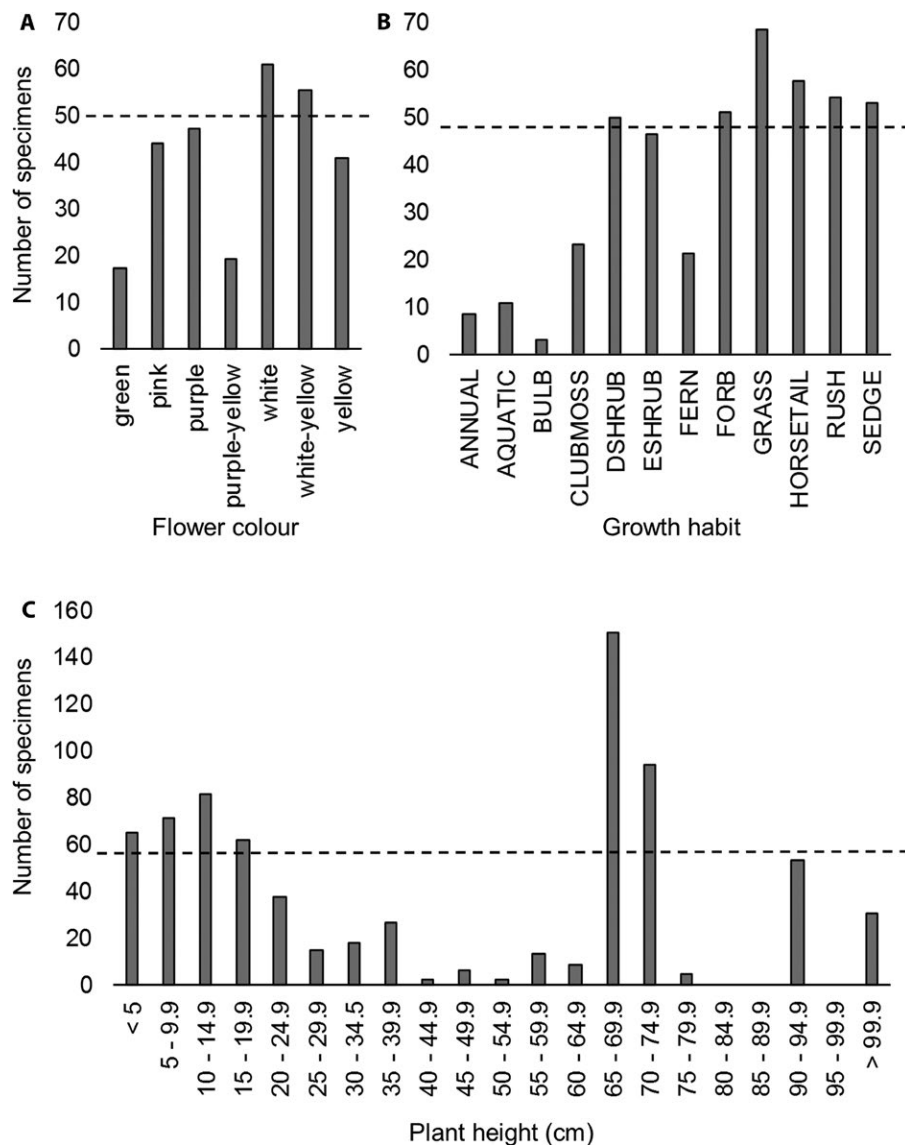
FIGURE 7. Normalised number of herbarium specimen records collected per flower colour (A), growth habit (DSHRUB = deciduous shrub and ESHRUB = evergreen shrub) (B), and plant height range (C) in Nunavut, Canada, and accessioned at the National Herbarium of Canada (CAN). In these graphs, the number of herbarium specimen records collected has been divided by the number of species per flower colour (A), growth habit (B), and plant height (C) present in the documented Nunavut florae, i.e., the counts have been adjusted to account for differences in the number of species per flower colour, growth habit, or plant height. Different bar heights reflect collection bias; no difference in bar heights would indicate no bias. Bars that extend above the horizontal dotted line are over-represented in the collection and those below the line are under-represented relative to the number of species of the flower colour, growth habit, or plant height present in the Nunavut florae.

under-collections were identified. Detailed pattern and bias analysis such as the one conducted in this study thus benefit herbarium institutions, providing an opportunity to upgrade data quality and identifying data gaps that can help to guide collection development and future analyses.

Conclusions

Biases in natural history collections should be taken into consideration when using specimens for phenological studies. We found collection biases related to particular time periods, phenological phases, easy points of access, taxonomic groups, flower colours, growth habits, and plant heights in an Arctic herbarium collection. Some of these biases differ from those in temperate and tropical regions and may arise from the challenges of Arctic travel. Thus, global and local political events, and current trends in science could have a pronounced effect on Arctic herbarium specimens available for phenological studies. Despite these challenges, Arctic herbarium specimens provide a valuable source of phenological data spanning considerable temporal and spatial scales. We recommend conducting an assessment, similar to the one in this study, to better understand the biases and limitations of the herbarium data set and to guide the phenological analyses.

AUTHOR CONTRIBUTIONS

Z.A.P. conceived the idea; collated, analysed, and interpreted the data; and wrote the initial draft of the manuscript. J.D. developed the ideas, interpreted the results, and edited the manuscript. H.M.K. and M.O.J. analysed and interpreted the data and edited the manuscript.

addition, as compared with temperate and tropical florae, the small size of most Arctic species often permits entire plants, or multiple plants, to be mounted on a single herbarium sheet, such that it is possible to assess the phenophase of one or more entire plants.

During the process of preparing data for analysis in this study, a number of data entry errors, particularly latitude and longitude, were identified and corrected. In addition, spatial and taxonomic

DATA ACCESSIBILITY

Data from the National Herbarium of Canada, at the Canadian Museum of Nature, are accessible via the Global Biodiversity Information Facility at https://www.gbif.org/occurrence/search. Data and image capture is ongoing over the long term. Updates appear weekly.

SUPPORTING INFORMATION

Additional Supporting Information may be found online in the supporting information tab for this article.

APPENDIX S1. Map of Nunavut showing the locations of all herbarium specimens (red circles; *n* = 26,281) and all "communities" (blue diamonds; *n* = 90) included in the analysis. "Communities" consists of year-round communities, research stations, weather stations, Canadian Forces bases, and Distance Early Warning (DEW) line sites. Size of all points for both specimens and communities was increased for visibility and does not accurately reflect the scale of coverage on the ground.

APPENDIX S2. Number, percentage, and cumulative percentage of herbarium specimens collected in Nunavut, Canada, and accessioned at the National Herbarium of Canada (CAN) by the top 88 primary collectors. The mean, start, end, range of years, number of years, and number of specimens collected per year are also given.

APPENDIX S3. Number of herbarium specimens, number of species, and observed and expected proportions per flower colour, growth form, and plant height collected in Nunavut, Canada, and accessioned at the National Herbarium of Canada (CAN).

APPENDIX S4. Correlation of year of collection versus day of year (DOY) of collection of all databased Nunavut specimens with an exact date of collection in the National Herbarium of Canada (CAN) (1947–2015). The black line represents the line of best fit (R^2 = 0.07, P < 0.0001, β = −1.8 days/decade, N = 28,427).

APPENDIX S5. Actual and expected number of herbarium specimen records collected per plant height in Nunavut, Canada, and accessioned at the National Herbarium of Canada (CAN) (1947–2015).

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