American Journal of Botany 93(4), 512–516 2006.

A NEW HERBARIUM-BASED METHOD FOR RECONSTRUCTING THE PHENOLOGY OF PLANT SPECIES ACROSS LARGE AREAS[1]

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Phenological data have recently emerged as particularly effective tools for studying the impact of climate change on plants, but long phenological records are rare. The lack of phenological observations can nevertheless be filled by herbarium specimens as long as some correction procedures are applied to take into account the different climatic conditions associated with sampling locations. In this study, we propose a new herbarium-based method for reconstructing the flowering dates of plant species that have been collected across large areas. Coltsfoot (*Tussilago farfara* L.) specimens from southern Quebec were used to test the method. Flowering dates for coltsfoot herbarium specimens were adjusted according to the date of disappearance of snow cover in the region where they were collected and compared using a reference point (the date of earliest snowmelt). In southern Quebec, coltsfoot blooms earlier at present (15–31 d) than during the first part of the 20th century. This phenomenon is likely associated with the climate warming trends recorded in this region in the last century, especially during the last three decades when the month of April became warmer, thereby favoring very early-flowering cases. The earlier flowering of coltsfoot is, however, only noticeable in large urban areas (Montreal, Quebec City), suggesting a strong urban heat island effect on the flowering of this plant. Herbarium specimens are useful phenological indicators; however, the databases should be carefully examined prior to analysis to detect biases or trends associated with sampling locations.

Key words: Asteraceae; climate change; flowering times; herbarium specimens; phenology; Quebec; *Tussilago farfara*; urban climate.

Phenological data have recently emerged as particularly effective tools for studying the impact of climate change on plants and animals (Menzel, 2002; Sparks and Menzel, 2002). During the last 10 yr, numerous studies from Europe (Fitter et al., 1995; Sparks and Carey, 1995; Sparks et al., 2000; Menzel et al., 2001; Ahas et al., 2002; Fitter and Fitter, 2002) and North America (Bradley et al., 1999; Beaubien and Freeland, 2000; Schwartz and Reiter, 2000; Abu-Asab et al., 2001) have shown, using historical phenological observations, that the onset of flowering times of many plant species occurs much earlier (3–55 d) at present than 35–100 yr ago. Most phenological data rely on observations from individuals who note, for a particular place over a long period, the first bloom of plant species. Long time series (>20 yr) and dense phenological observation networks exist in Europe, which facilitate the monitoring of flowering dates (Menzel et al., 2001; Ahas et al., 2002; Fitter and Fitter, 2002). The situation is very different on other continents: phenological records are usually highly dispersed, of short duration and limited to a few indicator species (Schwartz and Reiter, 2000).

The lack of long-term phenological observations can be filled by herbarium collections, especially in eastern North America where numerous plant specimens have been collected over the last century (Delisle et al., 2003; Prather et al., 2004a). For instance, Primack et al. (2004) compared the flowering dates of woody plant species using herbarium specimens sampled in New England from 1900 to 2002. Data from these specimens strongly suggest that plants flowered 8 d earlier from 1980 to 2002 than they did from 1900 to 1920. However, all specimens used in that study were collected at the same location (Arnold Arboretum, Massachusetts, USA), facilitating the comparison of flowering dates. There are probably very few places in North America where such extensive collections are available, thereby strongly limiting the use of herbarium specimens for phenological reconstructions. On the other hand, a large number of plant species has been abundantly collected throughout their distribution range. Bolmgren and Lönnberg (2005) have shown that flowering times derived from herbarium specimens correlate well with field data. Herbarium specimens could then be used to reconstruct flowering dates, as long as some correction procedures are applied to take into account the different climatic conditions associated with sampling locations. In this study, we propose a new herbarium-based method for reconstructing the flowering dates of plant species collected across large areas.

MATERIALS AND METHODS

Several studies have shown that spring-flowering plants respond more strongly to the climate warming trends of the last 100 yr than summer- or fall-flowering species (Schwartz and Reiter, 2000; Menzel et al., 2001, Fitter and Fitter, 2002; Sparks and Menzel, 2002). We consequently hypothesized that our herbarium-based method would be easier to develop using specimens of a spring-flowering plant. Among the hundreds of vascular plants blooming during the spring season in eastern North America, we selected coltsfoot (*Tussilago farfara* L.; Asteraceae) for this study because this exotic species is among the first plants to bloom in spring (Sparks et al., 2000), often just after the disappearance of the snow cover in the northern parts of its distribution range (Lamoureux, 2002). In Europe, the flowering of coltsfoot is mainly determined by the severity of the previous winter; a mild winter is usually followed by an early spring, which favors earlier flowering of the species (Sparks et al., 2000; Aasa et al., 2004). In North America, coltsfoot should respond rapidly to a shortening of the snow cover period, a phenomenon caused by climate warming that has already been observed in Europe (Ahas et al., 2002).

Although the distribution of coltsfoot in North America extends from North Carolina to Quebec and from Michigan to Newfoundland (Lamoureux, 2002), we focused our study on herbarium specimens sampled in Quebec, i.e., at the

[1] Manuscript received 7 June 2005; revision accepted 19 January 2006.

The authors thank A. Saint-Louis and M.-C. LeBlanc for laboratory assistance, Y. Jodoin for help with statistical analyses, J. Cayouette and three anonymous reviewers for comments on an earlier draft, and the numerous herbarium curators for their collaboration with this project. This research was financially supported by the Natural Sciences and Engineering Research Council of Canada.

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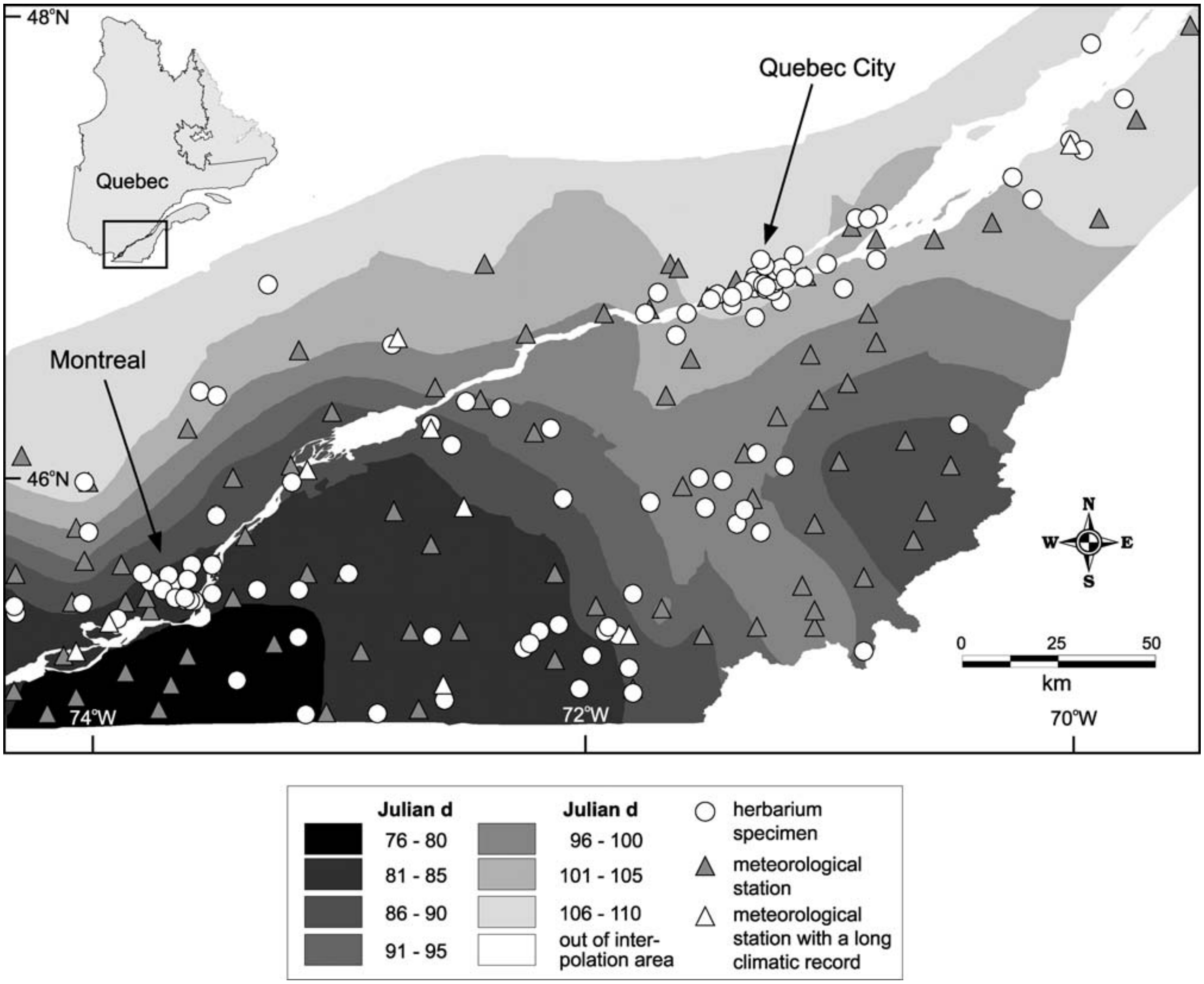

Fig. 1. Date (average for the 1971–2000 period) of the disappearance of snow cover in southern Quebec, Canada, reconstructed using climatic data from 88 meteorological stations. Only 5-d isolines are illustrated. The locations of herbarium specimens of coltsfoot (*Tussilago farfara*) used in this study are shown. Day 1 = 1 January.

northern limit of the range of the species. Preliminary sampling of coltsfoot herbarium specimens in all major herbaria (>100 000 specimens) present within the range of the species ($N = 39$) showed that southern Quebec (Fig. 1) was by far the region with the highest concentration of specimens ($N = 216$). Furthermore, data indicating the duration of the snow cover period—an important component of our study—were only available for the Canadian provinces (Environment Canada, 2005).

All specimens received from Quebec's herbaria (MT, MTMG, QFA, QUE, SFS) and from the two Canadian national herbaria (CAN, DAO) were examined to ensure the presence of fully opened flowers. Specimens with only flower buds or with fruits were excluded. The specimen number, sampling location, sampling date, habitat characteristics, and name of botanist(s) were recorded. Geographic coordinates (latitude, longitude) of sampling sites were localized as precisely as possible using the Topos sur le web database (Commission de toponymie du Québec, 2005). Specimens lacking precise information about sampling location or date were discarded. All data (sampling location and date) were incorporated into a geographic information system, MapInfo Professional (MapInfo, 2003).

The main problem associated with the comparison of flowering dates of specimens collected over large areas is the different climatic conditions associated with sampling locations (Bolmgren and Lönnberg, 2005). For example, a specimen sampled on 25 April may represent a very early-flowering event at the northern limit of the area, but a mid- or late-flowering case at the southern limit. Consequently, each collection date has to be adjusted according to its sampling location. For southern Quebec, we used a three-step approach. First, the spatial distribution of the mean date (1971–2000 data) of snow cover disappearance was reconstructed using climatic data from 88 meteorological stations (Environment Canada, 2005). The date of snow cover disappearance was the only available climatic variable with which an exact Julian date could be associated. Isolines of the date of snow cover disappearance were mapped by spatial interpolation using the Kriging method (Legendre and Legendre, 1998) and the Vertical Mapper software (MapInfo, 2004). Second, each herbarium specimen was associated with a particular date of snow cover disappearance according to its location. Third, the collection date of each herbarium specimen was adjusted using the equation $AD_i = (CD_i - SD_i) + SD_e$ (1), where AD_i is the adjusted collection date of the specimen i, CD_i the real collection date of the specimen i, SD_i the date of snow cover disappearance associated with the specimen i, and SD_e the date of snow cover disappearance of the zone with the earliest snowmelt. Julian dates (day 1 = 1 January) were used in this equation. In other words, flowering dates were adjusted according to the moment of the disappearance of snow cover and compared using a reference point (the date of earliest snowmelt). This procedure is similar to the displacement of all herbarium specimens to the same climatic zone and allows the comparison of flowering dates.

Once all the collection dates of herbarium specimens were adjusted, linear regression analyses of the evolution of flowering through time (in years) were

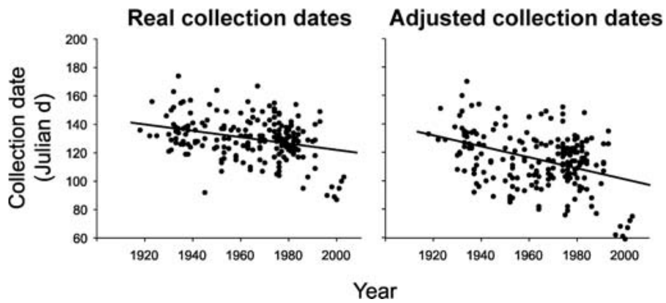

Fig. 2. Changes in flowering dates of coltsfoot (*Tussilago farfara*) over time reconstructed using herbarium specimens collected in southern Quebec. Reconstructions using real collection dates and adjusted collection dates, i.e., taking into account the date of disappearance of snow cover at each sampling location (see Methods), are shown. The line is the best fit line for the series. Day 1 = 1 January.

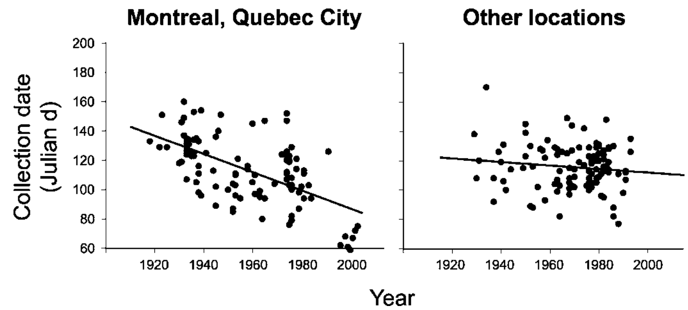

Fig. 3. Changes in flowering dates of coltsfoot (*Tussilago farfara*) over time reconstructed using herbarium specimens collected in Montreal and Quebec City and in other locations in southern Quebec. Adjusted collection dates are used in the reconstructions. The line is the best fit line for the series. Day 1 = 1 January.

performed. Box plots illustrating the temporal distribution of adjusted collection dates were also constructed for three different periods (1918–1955, 1956–1976, 1977–2003), each period having approximately the same number of herbarium specimens to facilitate the comparison (same sampling effort).

The so-called "urban heat island effect" may also influence the phenology of coltsfoot. In general, the mean temperature of an urban area is approximately 1°C higher than surrounding rural localities (Gallo et al., 2002), essentially because of (1) changes in the atmospheric composition, (2) changes in the radiation balance, (3) the production of heat by buildings, traffic, and industry, (4) the reduction of heat diffusion due to changes in airflow patterns, and (5) the reduction in thermal energy required for evaporation and evapotranspiration (Barry and Chorley, 1992). Two studies conducted in the eastern part of North America suggest that the urban heat island effect is important in this part of the world; the growing season for plants may be 8–15 d longer in urban areas than in adjacent rural areas (White et al., 2002; Zhang et al., 2004). We consequently compared (linear regressions, box plots) herbarium specimens collected in two of the three major (>150 000 inhabitants) urban areas of Quebec (island of Montreal and Quebec City) to those collected in other locations (small towns, villages, agricultural lands, forest lands, etc.) to detect any urban heat island effect on the flowering of coltsfoot. The third large urban area of Quebec (Gatineau) was not considered because no coltsfoot specimens were collected in this area.

The phenological reconstruction was compared to the evolution of the southern Quebec climate for the period covered by all herbarium specimens. Data from all meteorological stations in this region with a long uninterrupted climatic record (Brome, Drummondville, La Pocatière, Lennoxville, Les Cèdres, McGill University, Nicolet, Shawinigan, Sorel; Environment Canada, 2005) were used. The mean winter (December–March) temperature, the total winter snow precipitation, and the mean April temperature (daily maximum) were integrated in the model because previous studies have shown that these climatic variables have a strong influence on the flowering of spring blooming plants, especially coltsfoot (Fitter et al., 1995; Schwartz and Reiter, 2000; Sparks et al., 2000; Aasa et al., 2004; Primack et al., 2004). A weighted multiple linear regression (taking into account the number of herbarium specimens per year) was performed using the SPSS software (SPSS, 2001) to examine the temporal correlations between the flowering times of coltsfoot (mean of adjusted collection dates for each year with a record) and climatic variables.

RESULTS

In southern Quebec, coltsfoot bloomed from 27 March to 23 June. However, 90% of coltsfoot specimens flowered from 15 April to 31 May. A significant ($R^2 = 0.10$; $P < 0.001$) relationship (before the adjustment of the collection date) between flowering dates and time was found for the southern Quebec region (Fig. 2). According to this model, the coltsfoot blooming period occurred 19 d earlier at the beginning of the 21st century than around 1920. However, there is a clear southwest–northeast progression of the snow melting period each spring in southern Quebec (Fig. 1). The period during which the snow cover totally disappeared extended, on average, from 17 March to 20 April from 1971 to 2000. Adjusting the collection dates of herbarium specimens was consequently important; coltsfoot near Quebec City cannot bloom as early as individuals located near Montreal because of the late snowmelt. The adjustment procedure improved the model ($R^2 = 0.16$; $P < 0.001$). The model indicated that the coltsfoot blooming period in fact occurred 33 d earlier at the beginning of the 21st century than around 1920 (Fig. 2).

A significant ($R^2 = 0.36$; $P < 0.001$) relationship between flowering dates (adjusted) and time was found for the herbarium specimens collected in Montreal and Quebec City (Fig. 3). According to this model, the coltsfoot blooming period occurred 51 d earlier at the beginning of the 21st century than around 1920 in those two urban areas. No significant relationship ($R^2 = 0.01$; $P = 0.21$) between flowering dates and time was found for the herbarium specimens collected at other locations in southern Quebec.

Box plots provided a different perspective on the flowering dates of coltsfoot in southern Quebec (Fig. 4). When all specimens were considered, the median of the flowering period occurred 10–11 d earlier between 1956 and 2003 than during the 1918–1955 period. Very late-flowering cases were also more common in the first half of the 20th century than from 1956 to 2003. Conversely, very early-flowering cases were more common from 1977 to 2003 than from 1918 to 1976. However, as mentioned before, the trend toward an earlier blooming period was only noticeable in the Montreal and Quebec City urban areas: the median of the flowering period occurred 15–31 d earlier between 1956 and 2003 than during the 1918–1955 period.

The climate of southern Quebec became progressively warmer and less snowy during the 20th century (Fig. 5). The mean winter temperature rose by approximately 2.3°C, the mean April temperature (daily maximum) increased by 0.8°C (1.1°C from 1971 to 1990), and the total winter snow precipitation dropped by approximately 87 cm from 1970 to 1993. However, the mean April temperature (daily maximum) was the only significant ($P < 0.001$) climatic variable retained by the multiple linear regression model (adjusted $R^2 = 0.23$) that examined the temporal correlations existing between flowering times of coltsfoot and climate. Unfortunately, the lack of a long, uninterrupted climatic record in Montreal and

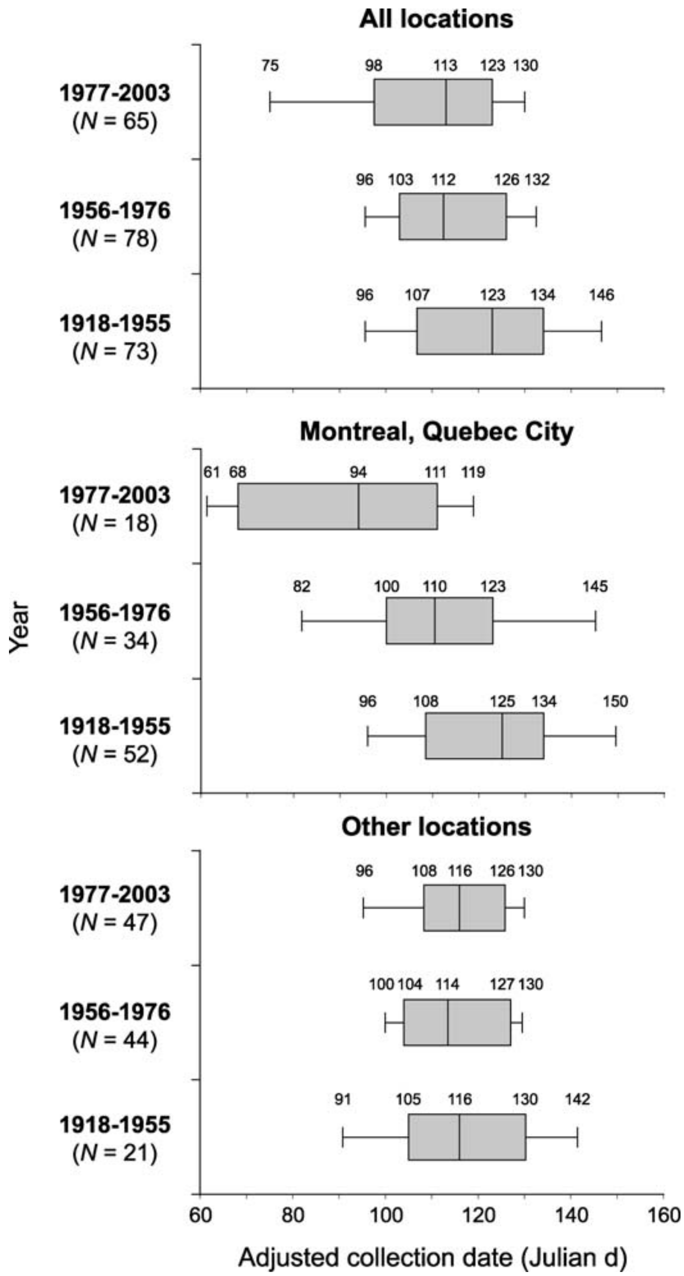

Fig. 4. Box plots illustrating the temporal distribution of adjusted collection dates of herbarium specimens of coltsfoot (*Tussilago farfara*) sampled in southern Quebec (all locations) or in Montreal and Quebec City and in other locations. Three different periods (1918–1955, 1956–1976, 1977–2003) are considered. For each period, the median (vertical bar), 25 and 75 percentiles (box) and 10 and 90 percentiles (error bars) are indicated. Day 1 = 1 January.

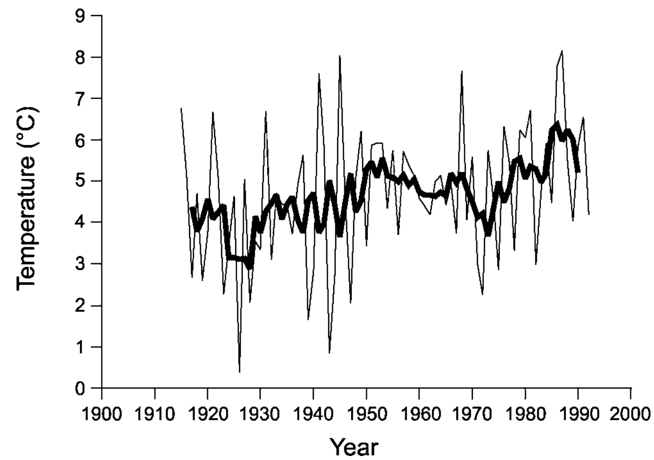

Fig. 5. Mean April temperature (daily maximum) during the 20th century in southern Quebec reconstructed using climatic data from nine meteorological stations (see Fig. 1 for location). The graph shows the mean of all stations. The bold line is the 5-yr running mean. Data sampled after 1995 are not shown (due to an excessive amount of missing data).

Quebec City precluded any specific analysis of the temporal correlations within these urban areas.

DISCUSSION

Reconstructing flowering dates using herbarium specimens collected over a large area is possible with adjustment procedures that account for the different climatic conditions at sampling locations. Our reconstruction of flowering dates of coltsfoot in southern Quebec has shown that this species is now flowering earlier (15–31 d) than during the first part of the 20th century. This phenomenon is likely associated with the climate warming trends recorded in this region in the last century, especially during the last three decades when the month of April became warmer, thereby favoring very early-flowering cases. This result is consistent with European data showing that coltsfoot bloomed 10–20 d earlier at the end of the 1990s than at the beginning of the 1950s (Ahas et al., 2002). The earlier flowering of coltsfoot is, however, only noticeable in large urban areas (Montreal, Quebec City), suggesting an urban heat effect increasing with population, a phenomenon already observed in several cities (Barry and Chorley, 1992). From 1921 to 2001, the population of the island of Montreal increased from 714 466 to 1 812 723 inhabitants and that of Quebec City (including suburbs) from 101 084 to 638 917 inhabitants (Linteau et al., 1989; Institut de la statistique du Québec, 2005). A different pattern has been observed in central Europe between 1980 and 1995: rural areas showed a greater trend towards earlier flowering than did urban areas (Roetzer et al., 2000). However, most European cities showed smaller temperature differences from rural areas than in North America, perhaps as a result of generally lower buildings and more densely populated rural areas (Barry and Chorley, 1992). In summary, herbarium specimens are useful phenological indicators, but a careful examination of the databases should be undertaken prior to analysis to detect biases or trends associated with sampling locations. For instance, the flowering of coltsfoot may be much more influenced by the location of individuals (urban) than by a general warming trend of the climate.

Although the method developed in this study allows the use of herbarium specimens collected at different locations throughout a large area, it should be used with caution. We noted that the number of herbarium specimens collected before 1930 and after 1990 was small. Differences in the timing of the collection of these specimens could accentuate the slope of the regression line. Furthermore, we knew that the most recent (1996–2003) specimens were collected by a botanist who systematically collected the first coltsfoot seen with flowers in his neighborhood. However, removing these specimens from the database did not change the significance level of the relationship between flowering dates (real or adjusted) and time ($P < 0.001$). Box plots are also less influenced by such sampling bias than linear regressions. Nevertheless, the most recent (1977–2003) part of the phenological record in Montreal and Quebec City is probably less reliable, especially because few herbarium specimens were sampled during this period. A long flowering duration (such as that of coltsfoot) may also bring additional problems to phenological reconstructions using herbarium specimens, but Primack et al. (2004) have shown that this aspect does not have a strong influence on results.

One major problem associated with the use of herbarium specimens for the reconstruction of flowering dates is the recent (20 yr) decline in plant collection, especially in Canada and in many parts of the United States (MacDougall et al., 1998; Delisle et al., 2003; Prather et al., 2004a). For instance, the lack of specimens from the 1990s and the 2000s, which are among the warmest decades of the last 100 yr (Folland and Karl, 2001; Sparks and Menzel, 2002), precludes any analysis of the most recent trends in the flowering of coltsfoot in southern Quebec. Consequently, our ability to predict how future climatic changes will affect our flora is increasingly limited (Prather et al., 2004b; Bolmgren and Lönnberg, 2005). Botanists should be encouraged to continue collecting herbarium specimens to avoid any further widening of the gap between the quality of past and recent biological records.

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