University of Alberta

Spring flowering trends in Alberta, Canada: response to climate change, urban heat island effects, and an evaluation of a citizen science network

by

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“We are so fortunate in this pursuit

Of renewed growth

Of ‘first blooms’ and ‘leaf outs’

That allows a sense of marvel at nature’s capacity for regeneration

Gladly we observe, with eyes open and senses keen,

Into the secret spaces

And well-known places

In search of spring’s return, and signs of awakening

Eager for the changes –

They are as much in ourselves

As in the tender shoots of coltsfoot or showy willow catkins

That brave the late snows, persevere, then thrive!”

– Spring Musings, by E. Slatter, Jasper (2010)

“I do think we gain immeasurably by participation in a survey of this kind. There is so much beauty in nature - that passes us by if we never learn to observe it.” – A. McKinstry, Oyen (1987)

“*With the changes in climate, I think it's important to help scientists document what's happening in the local plant communities. It's a small contribution plus it's easy and enjoyable. It helps to keep me attuned to the bio-community and I feel connected to a virtual world of other plant observers*.” – V. Demuth, fire tower watcher (2009)

Dedication

This thesis is dedicated to the over 650 Albertans who participated in Alberta PlantWatch starting in 1987. They freely contributed their time to observe and report plant development dates, and this invaluable information now provides clear evidence of the biotic effects of climate warming. These observers also contributed insightful comments on seasonal changes in weather as well as plants, birds, butterflies, bees, etc. They sent interesting questions, photos or plant specimens, comments on the program - and poems (see front page).

Observers were dedicated and persistent. The data received over the 20 years from 1987 to 2006 amounted to 47,000 records. Over half of those records were from observers who reported for a decade or more!

There are definite benefits from PlantWatching. Observers soon learn the normal sequence of plant ‘appearances’ in spring - that crocus blooms within a few days of aspen, and lilac follows chokecherry, which follows saskatoon, etc. This knowledge of nature’s calendar was once widespread. When Samuel de Champlain visited the Cape Cod area in 1605, first nations people advised him to “plant corn on the day the white oak leaf is the size of the red squirrel’s footprint”. Plant phenology can provide best timing for many activities, from planting the garden to planning a holiday for hiking or fishing.

Abstract

In documenting biological response to climate change, the Intergovernmental Panel on Climate Change used phenology studies from many parts of the world, but data from high latitudes of North America are scarce. This thesis reports climate trends and corresponding changes in sequential bloom times for seven plant species in the central parklands of Alberta, Canada (52–57° north latitude). The data span seven decades (1936–2006), drawing on historic Agriculture Canada data, observations by the Federation of Alberta Naturalists, and the Alberta PlantWatch program in both urban and rural areas of central Alberta.

An analysis of historical weather station data revealed a substantial warming signal over the study period (1936–2006), which ranged from +5.3°C for mean monthly temperature in February to +1.5°C in May. The earliest blooming species (*Populus tremuloides* and *Anemone patens*) advanced their bloom dates by two weeks over seven decades, while the later species advanced their bloom dates between zero and six days. Early-blooming species advanced faster than predicted by thermal time models, which may be due to decreased diurnal temperature fluctuations. This unexpectedly sensitive response resulted in an increased exposure to late spring frosts.

A criticism by climate change skeptics is that the observed warming signal is an artifact of the increasing heat island effect of growing cities. The current dataset offered the opportunity to test this claim due to the spatially and temporally extensive phenology database. The data indeed show an increasing heat island effect over the period 1931–2006 in both weather station data and plant phenology response. Across all seven plant species, the advance in phenology observed in Edmonton was 2.1 days (±0.9 SE) greater than in the surrounding rural areas over the last 70 years. This accounted for one third of the general warming signal, while the remaining advance of 3.7 days observed in rural settings was attributed to climate change.

Finally, as guidance for those initiating new observer networks, an analysis of factors that determined the quality of the PlantWatch phenological data was carried out. The thesis concludes with recommendations for effective volunteer training, observer motivation, and program protocols.

Acknowledgements

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My husband Geoff Holroyd helped with editing articles and kindly provided many hot suppers for a late-returning grad student! My generous father Jacques Beaubien had a love of science and the outdoors that informed and inspired me, and together we explored much of Canada including the arctic. My mother Miriam Beaubien passed on her photographic memory and a delight in wild plants and wild spaces.

Dr. Walter Moser, my MSc supervisor who in 1987 launched me on this phenological trajectory, continues to encourage my efforts. In recent years my writing group (composed of Anayansi Cohen, Esther Kamunya, and Xianli Wang) provided a wealth of help with writing, analysis, and presentations, plus encouragement and camaraderie. Dave Roberts also helped considerably with data analysis. Editing help included Myrka Hall Beyer, Linda Seale, and for observer communications: Linda Kershaw. Plant photographs used in presentations, webpages and publications were provided by Linda Kershaw and other botanists, PlantWatch observers, plus fellow provincial and territorial PlantWatch coordinators. Since 1996, I have enjoyed communications, workshops, and friendship with these coordinators. We all benefitted from help provided by Environment Canada's NatureWatch coordinator -- in recent years the highly effective Marlene Doyle. Alberta PlantWatch's webpage has been supported in recent years by Nature Alberta, in particular their technology wizard Vid Bijelic; his talents are appreciated.

Fellow students in our grad lab, the Spatial information systems (SIS) lab on the 8th floor of the General Services building, provided great conversation and company over the last six years. This evolving group has included Patrick Asante, Sharlene Becker, Marya Chechyna, Shibi Chandy, Shari Clare, Chen Ding, Derek Keeping, Kerri Lappin, Haitao Li, Andrea Macgregor, Michael Mbogga, Dave Roberts and Stefan Schreiber, and most recently: Katharina Liepe and Miriam Isaac-Renton.

International colleagues: since 1993 I have enjoyed conferences with phenologists in Europe and North America : including Annette Menzel, Mark Schwartz, Tim Sparks, Arnold VanVliet, Frans-Emil Wielgolaski and Alison Donnelly. Their friendship has been a great pleasure and their work an ongoing inspiration.

The PlantWatch program began in the Botany wing of the BioSciences building in 1987, and in 1991 moved to the Devonian Botanic Garden, encouraged by then director Dale Vitt. After 13 years in that idyllic setting, I moved back to the Biological Sciences in 2004 into office space kindly provided by Suzanne Bayley. Since 2007 this work has been based in the friendly Renewable Resources department. Many thanks to the talented PlantWatch assistants who helped me since 1991: Godo Stoyke, Ania Radziszewski, Karla Williamson, Trevor Lantz, Laura Frost, Krista Kagume, Malcolm Coupe, Colleen Nordlund, Tara Stewart, and Carmen von Conrad.

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Chapter 1 - Introduction

1.1 General background

Phenology, briefly defined as ‘the seasonal timing of life cycle events’ (Rathcke and Lacey 1985) is also defined as the study of the timing of recurring biological phases, the causes of their timing with regard to biotic and abiotic forces, and the interrelation of phases of the same or different species (Lieth 1974). Spring plant phenology is one of the most immediate and sensitive biological responses to climate variability and climate change, because it is mainly driven by air temperatures in temperate latitudes (Rathcke and Lacey 1985, Bertin 2008). Spring phenology is an important adaptive trait to balance full use of the growing season with avoidance of damaging frost events. Mismatches between spring weather and plant response can result in loss of early season growth and failure to produce fruit or seeds.

Phenology is also a potentially important adaptive trait in the context of climate change. For optimal growth, spring response should occur as early as possible, but late enough to avoid frost events that kill developing buds; thus plants are adapted to the local pattern of frost incidence and spring temperature variation (Rigby and Porporato 2008). Plants that cannot respond appropriately to changing climate by adapting their use of the lengthening growing season will be at a competitive disadvantage. There is some evidence that last frost events in spring are actually getting earlier faster than plant spring development, thus frost risk is decreasing.

Schwartz et al. (2006) found that for northern hemisphere terrestrial biomes last frost was earlier by 1.5 days/ decade (1955-2002), while first leaf dates were earlier by 1.2 days/ decade. Scheifinger et al. (2003) found similar results for frost events in Central Europe.

Global temperatures appear to have increased rapidly since at least the 1980's, in response to anthropogenic greenhouse gases. Of the 12 warmest years recorded since 1950, 11 occurred between 1995 and 2006 (IPCC 2007). The year 2010 was the warmest on record in Canada, at 3°C above the 30 year (1961-1990) normal (Environment Canada 2012). In this country the greatest temperature increase has been in spring and winter (Hengeveld et al. 2005). Daily minimum temperatures (night temperatures) have warmed more than daytime maximum temperatures (Karl et al. 2005). In Alberta, considerable climate change has been observed. Mbogga et al. (2009) found that over the last quarter century, the mean temperature of the coldest month has increased between 1.6 and 3.2 ºC, the mean annual temperature increased between 0.8 and 1.6 ºC, and precipitation was reduced by 12 to 24% for different regions in Alberta. But phenology datasets can serve as important evidence for climate change, independent from instrumental weather station data (IPCC 2007).

Phenology datasets have practical applications in many fields, including agriculture (timing of seeding, pest control, and harvest), human health (shifts in pollen seasons and allergies), and biodiversity conservation (timing of rare plant blooms, and timing synchronization of pollinators with open flowers). In temperate zones, both plants and insects develop in spring in response to heat accumulation, so plant phenology helps predict the timing of emergence of insect pests (Orton 1989). In forestry, the data are useful for fire prediction, insect and disease control, and as input to carbon sequestration models. Phenology data can further be used for modeling of forest growth (Rötzer et al. 2004), to define suitable habitat for tree species (Chuine and Beaubien 2001) and to guide seed transfers in future forests (Li et al. 2010). Ground-observed phenology can be used to validate satellite-derived dates for forest greenup, as in these studies using Alberta PlantWatch data (Beaubien and Hall-Beyer 2003) and Canada PlantWatch data (Kross et al. 2011). Phenological observations are needed to study climate feedbacks. Shifts to earlier springs and a longer growing season can affect climate through changes in vegetation, including longer photosynthetic activity and more carbon storage, as well as changed albedo and water balance (Peñuelas et al. 2009).

This thesis is based on plant phenology data from Alberta. As part of an MSc program in 1987, the author restarted an ‘Alberta wildflower survey’ that had recruited naturalist observers 1973 to 1982 (Bird 1983). Observers were asked to report on the following phenophases (growth stages) for up to 15 native plant species: first bloom (10% of flower buds open), mid-bloom (50%) and full bloom (90%) (Beaubien and Johnson 1994). In 2002, phenophase descriptions were updated to match European protocols better and the program was renamed ‘Alberta PlantWatch’ (Beaubien 2012) as part of the national Canada PlantWatch. The phenophase ‘first bloom’ was then defined as the date at which the first flower buds had opened in three different places on the observed tree or shrub or in a patch of herbaceous plants. The definition of ‘mid bloom’ did not change, and the stage of leafing was added for selected woody species. By 2010 the number of plant species observed in Alberta had increased to 25. This thesis is based on the data from 1987 to 2006, as well as historic databases dating back to 1936.

1.2. Environmental drivers of phenology

Towards the end of the growing season, the active period of photosynthesis and growth, perennial plants in temperate zones form their over-wintering meristem tissues (leaf and flower buds “set” on trees). Cued mainly by short days as well as cool weather, they make changes that permit them to survive the potential tissue damage associated with freezing temperatures. This process is called hardening. Hardened buds are dormant, and have little or no capacity for development towards budburst. Growth is inhibited despite exposure to thawing temperatures in winter. Release from this dormant state is possible once the plant has been exposed for an adequate period to chilling temperatures, which in Alberta likely occurs in autumn.

For many woody species, chilling temperatures to affect dormancy release have to range between 2 and 5 °C (Cannell 1989). A wider temperature range for native trees is reported by Hanninen (1991), where prolonged exposure to temperatures of -5 to +10 °C was needed to attain growth competence for buds. Sufficient chilling means that the woody plant can respond quickly to spring warming temperatures, with swelling of buds and budburst. Release from dormancy involves a series of physiological internal changes leading to the state where buds are fully able to develop (Hänninen 1995). In experimental studies, dormancy is considered ‘fully released’ when further chilling has no significant effect on growth after a fixed time in a warm place.

In areas of mild winter temperatures (e.g. west coast of British Columbia) chilling is essential to prevent response to frequent warm periods in winter, so these populations tend to have a high chilling requirement. In more continental climates, such as Alberta, chilling of *Populus tremuloides* appears to be complete by December (personal communication, Simon Landhäusser, September 2012), and thus this species can react to temperature with no hesitation in spring. Boreal trees in Alberta likely have small if any chilling requirements, which are satisfied before winter. Myking (1995) found that birch in Scandinavia would still have adequate winter chilling even with climate warming up to 8 °C. They concluded that climate warming would bring earlier plant budburst and more risk from frost, especially for birch farther north.

Subsequent to dormancy release, the timing of spring flowering for perennial plants in temperate zones is largely driven by accumulated temperature above a threshold value (Rathcke and Lacey 1985). Air temperature is also considered the main driver for leaf emergence in temperate deciduous trees (Lechowicz 1984). This accumulated temperature or thermal time is expressed in degree-days (DD), calculated by the daily addition of mean temperatures above a base or threshold value (often 0 to 5 ºC for early spring blooming species). This addition continues up to the day of the phenophase event (e.g. date for first pollen shed of aspen), yielding a ‘heat sum’.

1.3. Thermal time models of spring phenology

Models describing the biological mechanisms of hardening, chilling, and dehardening generally involve a small number of parameters. Researchers test a range of values for the parameters ‘base temperature’, which influences the rate of the heat sum accumulation, and ‘starting date’ which estimates the date when chilling is complete. The optimal parameter values are selected by trial and error, evaluating which yield most consistent heat sums for an observed event such as budbreak or first bloom (Lindsey and Newman 1956, Boyer 1973, Di-Giovanni et al. 1996).

Thermal time models of spring phenology make a range of assumptions and have a number of technical differences. Studies vary with respect to the temperature variable used in summation. Using maximum daily temperatures has the benefit of measuring all the heat available to the plant, but omits any component of duration. Using mean daily temperatures reflects both low and high temperatures, but some usable heat is not included in the summation if the daily mean falls below the threshold value. It is tedious but also more accurate to estimate the durations of temperatures between the daily maximum and minimum (Lindsey and Newman 1956). Hunter and Lechowicz (1992) used a sine wave method to describe diurnal temperature variation to calculate degree days using daily max/min temperature data.

Most studies assume a linear thermal time relationship, where all thermal units or degree days above a base temperature have an equivalent effect in advancing buds towards budburst or bloom. These thermal units are added up as in the following invented example which uses a selected threshold of 2 ºC: on the start date of April 1, the mean temperature is plus 8. We subtract the threshold temperature 2 from 8 and start our summation with 6 growing degree days. On April 2, 9 DD are added, and on April 3, 2 DD and so on for each day where the mean is above the base temperature. Summation stops on the day of the phenophase event e.g "first bloom" or "leafing". This value of heat sum for a species' phenophase varies to a degree depending on location and whether it is an early or late spring (Boyer 1973). More heat tends to be required by a species to bloom in warmer early springs (Lindsey and Newman 1956, Diekmann 1996). In a cold spring, temperate zone plants eventually bloom despite lower than usual temperature accumulation, likely due to activation of a photoperiod cue (Menzel et al. 2005).

The thermal time model is conceptually driven by the temperature of the meristematic plant tissues, not air temperature. While air temperature is usually the only available measurement, the model can be improved by including the influence of solar radiation because bud temperatures are higher than air temperatures on sunny days (Landsberg et al. 1974). Adding sunshine hours or solar radiation to models of plant response can improve the estimate of budburst dates. Caprio (1974) used lilac data to devise "solar thermal units" (STU), combining heatsums above a threshold of -0.5°C with solar radiation, to calculate the amount that plants needed to flower. Lilacs, no matter whether grown in cloudy Norway, sunny Montana or on the west coast of the United States required 380,000 STU to flower. On the other hand, White (1979) found that adding solar radiation to temperature did not explain any more variation in the bloom times of 53 rangeland plants.

Other factors may influence the date of budbreak in temperate zones. It has been shown experimentally that long day lengths can replace chilling (Campbell and Sugano 1975, Cannell and Smith 1983). In general, photoperiod is a minor factor in spring, but plays a greater role in the timing of late summer stages such as fruiting and leaf colouring (Larcher 2003). Secondly, soil temperatures may be important, though they show a linear relation to increasing air temperatures (Cannell and Smith 1983). Third, soil moisture can mediate plant response to temperature. If plants are exposed to drought in spring, budbreak may be delayed (Idso et al. 1978). Conversely, Cleland (2006) reported that increased precipitation had no consistent phenological response in experimental manipulations of a California grassland. Most research shows that moisture seems to have little effect on phenology in temperate zones (Menzel 2003). But it must be noted that precipitation has far more spatial and temporal variability than temperature and thus it is harder to identify its influence on plant phenology (IPCC 2007).

Lastly, CO_2 concentrations may influence phenology. In a California grassland, experimentally-elevated CO_2 delayed grass bloom and accelerated forb bloom (Cleland et al. 2006). But in greenhouse experiments with *Pinus sylvestris* seedlings, elevated CO_2 had no effect on budburst timing (Hanninen 1991). In summary, other abiotic factors besides air temperature may affect spring plant phenology but accumulated temperature is by far the most important direct driver of spring phenology in temperate areas. An extensive literature review on plant phenological cues (e.g. temperature, precipitation, photoperiod, irradiance etc.) has recently been assembled at the National Centre for Ecological Analysis and Synthesis in California (Wolkovich 2012).

Biotic drivers of phenology must also be considered, affecting a genetic response. Bloom timing is influenced by pressures from pollinators or seed dispersers, as well as predators that consume flowers or seeds (Elzinga et al. 2007). The ability of a plant to flower at the 'right' time is crucial to maximize reproduction via exposure to pollinators (spring winds or insects) and to exploit best the available growing season to produce seeds.

1.4. Species differences in thermal time response

An example of a particularly well-studied woody species is *Syringa vulgaris* (common purple lilac). This ornamental, widely-cultivated shrub is used internationally by phenology networks, including Canada PlantWatch (Environment Canada 2010). A study of lilac bloom dates from 251 locations in the USA found the coefficient of variation of thermal time to flowering was smallest using a base temp of -0.6º C (Caprio 1974). Examples for well-studied boreal species include pines, included in the Alberta Plantwatch program since 2000. Di-Giovanni et al. (1996) researched timing of operations to reduce pollen contamination in pine seed orchards. They found for maximum pollen release of *Pinus banksiana* (jack pine) from 3 northern Ontario locations, the best combination was a base temperature of 4ºC and start date of April 17, with a resulting heat sum of 288.6 degree days.

Base (or threshold) temperatures for heat sum accumulation for budbreak and bloom differ among plant life forms and geographic regions. In the Earth's temperate zone, threshold values often range from 0-5°C for woody plants. Herbaceous plants generally have higher base temperatures of 6-10 ºC, but these are lower (0-6 ºC) for spring ephemerals and alpine plants. Leafing in some species of *Populus* can occur at temperatures as low as 0 ºC (Larcher 2003). While the heat sum requirements for a stage such as first pollen shed are relatively constant for a plant species among years, location is important. Single species studies show that populations at higher latitudes or altitudes tend to respond more quickly to spring increases in temperature (Li et al. 2010). This is likely an adaptation to a shorter growing season.

Species react independently to climate warming (Sparks and Carey 1995, Abu-Asab et al. 2001) but generally species that bloom in early spring are more sensitive to and thus better reflect changes in temperature (Menzel et al. 2006). *Populus tremuloides* (a tree) and *Anemone patens* (herbaceous forb) are two species that start the PlantWatch bloom sequence. These two "start of spring" Alberta plants generally bloom within 2 days of each other and flowering occurs soon after snowmelt. But in years of deep spring snow, tree buds can respond to rising temperatures more quickly. In these years *Populus* may have a smaller heat sum and earlier bloom than *Anemone*. Therefore the interaction of plant life form and snow depth may influence spring phenology in Alberta.

For a given location, the sequence of phenological events is very uniform, and thus the timing of one event can predict the subsequent timing of an event for that or another plant species. In Edmonton, the two shrubs *Amelanchier alnifolia* (saskatoon) and *Prunus pensylvanica* (pin cherry) generally start bloom within one day of each other (unpublished data). Delbart et al. (2005) found a tight correlation between woody species events using remotely sensed data from Siberia: the mean difference between leafing times for *Betula* (birch) and *Populus* *tremula* (a close relation of the North American *P. tremuloides* and also called 'aspen') was 3 days (SD = 4.7). At the start of the growing season both flowering and leafing events are highly correlated, and therefore sub-canopy flowering events can be used to predict the timing of forest green-up.

This review has focused on perennial plants, which were selected for phenological study in Alberta as they persist for years in a location and develop in response to increasing temperature. In contrast to perennials, annual plants' bloom times depend somewhat on when the seed germinated and plant growth began. For many herbaceous annual plants including some grass species, photoperiod is the cue for flowering. But as photoperiod is unchanging from year to year for any specific location and date, any trend in spring blooming time for an annual plant would indicate that other factors are important.

1.5. Documentation of climate change

Due to its direct dependence on temperature and because it is readily observable, spring phenology in temperate zones has served as important source of evidence for climate change. The majority of global phenology data are from Europe. Menzel (2000) analysed data from cloned woody plants (13 trees and 3 shrubs) from International Phenological Gardens across Europe (1959-1996). Over this period, spring events including leaf unfolding and flowering advanced by 2 days/decade. In Estonia, Ahas (1999) found that plant bloom times for 1952-1996 (45 years) advanced from 1.4 to 2.9 days/ decade. Fitter (2002) examined first bloom dates (1954 to 2000: 47 years) for 385 British plant species (grasses, forbs, woody plants) and noted an advance of 4.5 days in the recent decade (1991-2000) as compared to the previous 37 years; this translates to a shift of 0.9 days earlier/ decade. A major review that includes the above papers summarized 254 mean national time series from 21 European countries (1971 – 2000) and concluded that the mean advance of spring and summer was 2.5 days per decade (Menzel et al. 2006). The phenology patterns closely matched the warming noted across 19 countries. But there was no indication of plants adapting to climate warming; in a comparison of phenology records across the 20th century in Germany, plant species' response to temperature did not change over time (Menzel et al. 2005).

A review of global phenological studies over the last century revealed a 10-20 day lengthening of the growing season over the last few decades, with the largest trend to earlier spring onset (Linderholm 2006). In the mid-1970's there was a shift to increasing temperatures, reflected in a shift to earlier phenological development on a wide scale (Walther et al. 2002). An excellent review by Bertin (2008) summarizes published studies and notes generalizations including the following: a) early spring stages show greater advances over time than later stages, b) abundant spatial variation in phenological shifts has been reported, and c) species differ in their phenological response.

In North America, Abu-Asab (2001) noted mean first flowering advances of 0.8 days/ decade for 89 of 100 angiosperm species in Washington, DC, over the years 1970 to 1999 (30 years). These were correlated with increases in minimum temperature. Bradley et al. (1999) compared bird and plant data for Aldo Leopold's cabin over six decades 1936-1998, with a 30-year gap after the first decade. Of 21 plant species starting bloom before June 1, six species showed regressions with statistically significant trends to earlier bloom. Averaging all 55 phenophases showed a shift to earlier development by 1.2 days/ decade. For the western USA, trends over 38 years (1957-1994) were 2 days/ decade earlier for first bloom of *Syringa vulgaris* (common purple lilac), and 3.8 days/ decade for *Lonicera* sp. (honeysuckle) (Cayan et al. 2001). They also noted increasing spring temperatures of 1-3 ºC and earlier streamflow pulse dates beginning in the 1970s.

In Canada, Houle (2007) used herbarium specimens and found a 0.2 to 0.6 days/ decade shift to earlier bloom over 100 yrs (1900 to 2000) in three areas of Quebec and Ontario, for 18 spring flowering herbaceous plants. This study also found a 2-3 day advance/ ºC increase, and evidence of a heat island effect for Montreal. In Edmonton, Alberta, a ‘spring flowering index’ which combined responses of three woody species showed an 8 day shift to earlier development over the period 1936-1996: 61 years, ie 1.3 days/ decade. The earliest appearing species, *Populus tremuloides*, showed a doubling of this trend: 2.6 days/ decade over the 20th century (Beaubien and Freeland 2000). There is a relative scarcity of published data on trends in phenology in North America.

Comparing trends from various studies is challenging as they vary with respect to species, phenophases, time span, and geographic area. However, the literature paints a common picture of changes in spring timing. In Europe, spring phases are earlier by 1.2 to 3.1 days/ decade and in North America by 0.8 to 3.8 days/decade (Menzel 2003). Generally, ground-based studies show a shift to earlier spring of 2.3 to 5.2 days / decade over the 3 decades up to 2006 in response to warming, confirmed by remote sensing studies (IPCC 2007).

1.6. Heat island effects

The urban heat island effect poses one potential technical problem in interpreting the causes of observed trends in spring plant development timing. Many of the published phenology data are from urban centres, where conditions are warmer than in the surrounding rural areas. This heat island effect is caused by the absorptive and radiative properties of roads and structures, as well as emissions from heating, industry and vehicles (Defila and Clot 2003). To study the changing influence of city size, population statistics are often used (Barry and Chorley 2010).

In central Europe, spring phenophases for early spring phases in 10 city locations (1980 to 1995) were four days earlier than in rural locations, and trends were larger trends in more recent years (Rötzer et al. 2000). In eastern Canada, analysis of herbarium specimens of *Tussilago farfara* (coltsfoot) showed major shifts to earlier bloom of 15-31 days since the early 20th century, in the cities of Montreal and Quebec (Lavoie and Lachance 2006). No trend was found for rural areas. This would indicate that in cold climates this urban effect is considerable and needs to be addressed in our analyses. As well, urban systems provide surrogates for studies of climate change, to help predict the impacts of future increasing temperature and CO_2 levels.

1.7. Protocols for phenology observation programs

There are several different methods to conduct phenological studies. The simplest type of survey is an annual "snapshot" study, where many observers survey plant development stages over a large area at a specified date (e.g. the “May Species Count” by Nature Alberta). Another survey type makes use of large networks of volunteers that record specific growth stages or phenophases on selected species whenever they occur (e.g. Canada PlantWatch, or the German Weather Service phenology observation program). Some studies are restricted to expert observers and researchers that make use of repeat observations on tagged plants, which usually results in better data quality. Other sources for phenology data that can contribute to studies of long-term trends in phenology include historic explorer’s journals, herbarium records, daily pollen count data (from medical researchers), and for recent decades: satellite observations.

Phenological data are relatively simple to record, and extensive datasets from amateur and professional observers have been assembled in many parts of the world. Phenology studies have seen a resurgence of interest and many new volunteer networks have been initiated in recent decades. These include the federal expansion of Canada PlantWatch (Environment Canada 2010), Britain’s program to track phenology of plants and animals (Woodland Trust UK 2012), and the Netherlands ‘nature’s calendar” (Milieusysteemanalyse 2012). The USA National Phenological Network had its official launch March 2009 (USA-NPN 2012). Aspects of phenology globally including history, networks, research by taxa or biome, modeling, and applications including remote sensing are described in two “bibles of phenology” (Lieth 1974, Schwartz 2003). PlantWatch in Canada is potentially a very useful tool to help Canadians understand, mitigate, and adapt to the expected changes in climate as well as the potential impacts on biodiversity and society. Since 2000, the author has been science advisor for the national program Canada PlantWatch (Environment Canada 2010). The history of phenology in Canada is described in Beaubien (1991) and (Schwartz and Beaubien 2003).

Sources of variation in phenology data include the plants (genotype), the observer (skill and experience), the site (geographic location and microclimate), and the weather (Beaubien 1991, Beaubien and Johnson 1994, Schaber 2002). The influence of temperature is strongest for early-blooming spring species (Beaubien and Freeland 2000, Menzel et al. 2006), and thus these may be the best species to track for climate change studies.

1.8. Thesis structure

In this thesis, I quantify plant spring phenology of up to 25 plant species in response to climate and climate change in Alberta. Available data include 20 years of field data collected by myself and provincial volunteers 1987–2006, plus additional databases for the periods 1936–1961 and 1973–1986 from other researchers. My goal is to determine (1) how different species have responded to climate change over the last seven decades, and (2) how heat island effects may exaggerate the climate change response in the city versus rural areas. Because new phenology survey networks continue to appear in the United States and Europe, I will further develop recommendations on observation protocols, species selection and quality control based on a quantitative analysis of the Alberta PlantWatch volunteer network.

My aim for ***Research Chapter #1: Long-term trends in spring phenology*** is to document changes in timing of first bloom for seven plant species using phenology data from three sources for Alberta's central parkland from 1936 to 2006. In this chapter I will also attempt to build a predictive model of abiotic drivers of spring phenology and test whether additional factors that are not usually part of thermal time models contribute to spring phenology for these plant species. For herbaceous species, snow depth may influence the timing of spring flowering. Frost events may damage reproductive tissues and thus prevent or delay flowering. Lastly, I ask whether changes in plant-climate synchronization could create potential problems for future plant survival. For example, aspen is said to bloom in general a month before the last killing frost. In springtime is the timing of last frost shifting at the same rate as the plant response? To detect which species may be most vulnerable to observed and projected climate change, I investigate trends in timing of last spring frosts.

The ***Research Chapter #2: Heat island effects*** looks at potential bias in phenology trends that may emerge due to observation location. Urban environments are often warmer than rural areas due to anthropogenic changes, causing shifts to earlier plant development in spring. This urban heat island effect is additive to the general pattern of climate warming, and may confound an understanding of its effects if urban population growth takes place at the same time as general climate warming. Therefore, studies of plant response both inside and outside urban centres are needed to disentangle these two potential causes of shifts in plant timing. In this chapter I will analyze the heat island effect in Edmonton, Alberta, based on rural and urban weather station records for the period 1916 to 2004, as well as urban phenology records for the period 1936-1961 and rural and urban phenology records 1987-2006. I will attempt to visualize the urban heat island effect via spatial interpolation for 1987-2006 data, with comprehensive spatial coverage, and I will further try to quantify what proportion of the overall warming effect relative to the 1936-1961 period is attributable to an increasing heat island effect (due to population growth and urbanization), rather than to climate warming.

The goal of my ***Research Chapter #3: Plant phenology for citizen scientists***, is to develop better methodologies and more robust observer protocols for the Canada PlantWatch program and similar efforts elsewhere. I will review options for both selection of species and growth stages for observation, as well as for recruitment and training of observers. I will make recommendations on the best plant species and phases to track climate change, and recommend how to design studies to minimize observer error and maximize data quality. I will look for correlation between ease of observation of plant species and phenophases, and reporting accuracy. Better quality data might be expected for plant species that are abundant and widespread, lack similar-looking species, have conspicuous flowers, and have a short blooming period in spring. Secondly, I will analyze whether the supplementary microhabitat data gathered by the Alberta PlantWatch program (e.g. location slope and aspect, distance to buildings, etc.) improved the accuracy of observations. Finally, I will investigate whether experienced long-term observers provide better data (i.e. data that correlate better with climatic factors) than short-term observers. I synthesize the results to help those who wish to initiate new observer networks regarding observer recruitment and training, effectiveness of program protocols, and selection of species and bloom stages.

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Chapter 2 - Spring Flowering Response to Climate Change between 1936 and 2006 in Alberta, Canada [1]

Summary

In documenting biological response to climate change, the IPCC has used phenology studies from many parts of the world, but few are available from high latitudes of North America. Here, we evaluate climate trends and corresponding changes in sequential bloom times for seven plant species in the central parklands of Alberta, Canada (latitude 52–57° north). We found a substantial warming signal over the study period of 71 years (1936–2006), which ranged from an increase of 5.3°C in the mean monthly temperatures for February to an increase of 1.5°C in those for May. The earliest-blooming species' (*Populus tremuloides* and *Anemone patens*) bloom dates advanced by two weeks during the seven decades, whereas the later-blooming species' bloom dates advanced between zero and six days. The early-blooming species' bloom dates advanced faster than was predicted by thermal time models, which we attribute to decreased diurnal temperature fluctuations. This unexpectedly sensitive response results in an increased exposure to late spring frosts.

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2.1 Introduction

The scientific field of phenology, defined as the study of the seasonal timing of life cycle events, has seen a recent revival with climate change being a prominent issue. Sparks and colleagues (2009) noted that the use of the term ‘phenology’ in the scientific literature has become seven times more common between 1990 and 2008. In documenting biological response to global climate change the Intergovernmental Panel on Climate Change (IPCC 2007) has relied on phenology studies as compelling evidence that species and ecosystems respond to global climate change (Rosenzweig et al. 2007). Particularly for perennial plants in temperate zones, temperature exposure over time is the main driver for spring development, including the timing of bloom and leafout (Rathcke and Lacey 1985, Bertin 2008). This makes spring phenology one of the most sensitive, immediate, and easily-observed responses to changing climate in temperate regions (e.g. Schwartz et al. 2006).

The use of phenology observations to document climate variability and climate change has a long history. In 1956, Arakawa published an article entitled “Climatic change as revealed by the flowering dates of the cherry blossoms at Kyoto”. He analyzed a long-term record of dates when the emperor held the annual cherry blossom festival that reached back to the ninth century (Arakawa 1955, 1956). Remarkable phenology records covering more than two centuries also exist for European countries, starting with observations by Linnaeus in the 18th century (Parmesan 2006). In a meta-analysis for Europe, Menzel and colleagues (2006) compiled an astonishing 125,000 time series recorded for more than 500 plant species in 21 countries.

Although a number of famous historical figures have been involved in early, systematic phenology observations, including Thomas Jefferson as well as Henry David Thoreau and Aldo Leopold (Stoller 1956, Miller-Rushing and Primack 2008), long-term records of phenology observation are comparatively scarce in North America when compared with Europe (Schwartz and Beaubien 2003). A notable analysis was carried out by Aldo Leopold’s daughter N. L. Bradley and son A. C. Leopold. They compared Aldo Leopold’s 1935–1945 Wisconsin farm records (Leopold and Jones 1947) with data on 36 plant species collected in the same area from 1976 to 1998 (Bradley et al. 1999). Another major long-term observation effort is the phenology network established by Caprio (1957), recording phenology of lilac (*Syringa vulgaris*) and honeysuckle cultivars (*Lonicera* spp.) with the help of local garden clubs in 12 western US states until 1994 (Cayan et al. 2001). A similar lilac-honeysuckle network, which still exists today, was established in 1959 in the northeastern US states and eastern Canadian provinces (Schwartz and Reiter 2000). However, there is a notable lack of phenology data for western Canada and Alaska where the spring warming signal over the last 50 years has been most pronounced globally (Rosenzweig et al. 2007).

Besides documenting global change, trends in plant phenology can reveal important ecological consequences associated with climate change (Parmesan 2006, Cleland et al. 2007). Plant populations are finely tuned to local frost risk environments at the beginning and end of the growing season, and phenological traits are usually highly heritable and often subject to strong selection pressures (Campbell and Sugano 1975, Vitasse et al. 2009, Li et al. 2010). The timing of spring plant development balances the need to avoid damage due to late spring frosts while maximizing the use of the available growing season in competition with other species (Lechowicz 1984, Leinonen and Hanninen 2002). Therefore, plants at northern latitudes and at high elevation break bud relatively early, i.e. the need to utilize the growing season takes relative precedence over avoiding late spring frost damage. This has been documented in many common garden studies for wide-ranging plant species (reviewed by Li et al. 2010).

The timing of spring development in virtually all temperate perennial plants is primarily controlled by temperature (Rathcke and Lacey 1985, Hunter and Lechowicz 1992). Plants require a certain amount of exposure to warm temperatures before leafout or flowering occurs. Exposure to warm temperature over time can be measured in degree days, which is the sum of average daily temperatures above a base value. A common base temperature is 5°C, which is widely used to calculate growing degree days in agriculture. For a given species, this amount of warm temperature over time, referred to as required heat sum, is largely constant and can be used to predict bloom times from daily temperature records in what is called a thermal time model (Bertin 2008). The required heat sum for spring development is a genetically controlled adaptive trait (Leinonen and Hanninen 2002). Heat sum accumulation allows plants to respond to an unpredictable onset of the growing season, which can easily vary by a month in northern latitudes.

If spring development were exclusively driven by exposure to warm temperature, climate change would not affect the match of plant development with the available growing season. However, additional factors are known to modulate the timing of spring development. Photoperiod may delay bud break if warm temperatures arrive unusually early (Menzel et al. 2005). Some plants also require a certain amount of exposure to cool temperatures following bud set in fall before they start development in response to warm spring temperatures. This is referred to as a chilling requirement, which is measured by summing exposure to moderately cool temperatures, typically between 0 and 10°C. This is thought to guard plants from prematurely breaking bud during mid-winter thaws. In both cases climate warming would be expected to delay spring response. Plants may be constrained by photoperiod effects that prevent early development, or in warmer regions they may not receive sufficient exposure to cold temperature to release them from dormancy (Bertin 2008).

Another factor that impacts spring phenological response at high latitudes and high elevation is the prevalence of snow (Inouye and Wielgolaski 2003, Wielgolaski and Inouye 2003). A deep spring snowpack further shortens the growing season and once the snow has melted plant response is often immediate, suggesting very low heat sum requirements, and making the release from snow a primary driver of spring phenology. This also has important implications for the effects of climate change. A smaller snowpack due to either higher temperatures or less precipitation would lead to earlier release from snow, an earlier start of plant development, and potentially higher frost exposure (Inouye 2008).

In the present article, we report results from spring flowering observations conducted over approximately seven decades (1936–2006) in Alberta, western Canada. We analyzed first bloom dates for seven plant species that come into flower in a temporal sequence between early April and June. The first objective of this study was to attempt to provide evidence of plant response to global climate change for a higher latitude location of western North America, a region where long-term data coverage is scarce. Secondly, we asked whether phenology trends correspond to observed temperature trends according to spring thermal time models, or alternatively, whether other factors influence spring development, which would potentially lead to altered sequences of bloom time. Finally, we investigated whether shifts in bloom time have led to changes in exposure of species to late spring frosts.

2.2 Phenology observations in central Alberta

We evaluated observations from a phenology network across the central parkland of Alberta (figure 2-1). This ecological subregion covers approximately 50,000 km² and is situated between the boreal forest to the north and the warmer and drier grasslands to the south. The native vegetation consists of open forests dominated by two poplars (*Populus tremuloides* Michx. and *Populus balsalmifera* L.), white spruce (*Picea glauca* [Moench] Voss) and birch (*Betula* spp.) as well as prairie vegetation found under drier microsite conditions. However, much of the native vegetation has been converted to agricultural use because the area has some of the best soils in Canada. Intensive phenology observations began in 1936 with a program by Agriculture Canada, in which the timing of wheat development as well as bloom times for 50 native plant species were recorded over 26 years. The purpose of this program was to identify indicator events to guide the timing of agricultural activities (Russell 1962). This program ended in 1961, which resulted in a data gap of 11 years before botanist Dr. Charles Bird initiated a new research program, which tracked bloom times for 12 native species between 1973 and

1986. The data were collected by a network of citizen scientists (Bird 1983) supplemented by Bird's own observations (figure 2-1). This network was extended by EB in 1987, and in its current form, the volunteer observers record data for one or more of 25 species (plantwatch.naturealberta.ca). Since 1987, this network has collected data from approximately 650 observers, with up to 240 observers reporting each year. The plant species for this phenology network were selected primarily based on the plants' wide distribution and short bloom period in spring, the ease of their identification by citizens, and the lack of similar-looking species. For additional background on these data series, see Beaubien and Johnson (1994) and Beaubien and Freeland (2000).

This study evaluates the dates of first bloom for several plant species. First bloom was defined as a plant stage where the first flower buds had opened in an observed tree or shrub, or in a patch of smaller plants. We requested that the observers report on plants that were situated in flat areas away from heat sources such as walls of houses. Observers were asked to select plants that approximately represented the average bloom time for that species in their area (i.e., that were not the first or last of that species to bloom). Therefore, our first bloom data do not represent the earliest-blooming individuals of a population (as in Miller-Rushing et al. 2008). Rather, it is a developmental stage sampled to represent a local population. Generally, the first bloom stage is simplest to observe and yields more temporally-precise data than later bloom stages, which can be harder to estimate. Because many of the data (1987–2006) were compiled from multiple individual plant observations, we used the annual mean bloom date from all available points in the central parkland. The annual first bloom dates were compiled by species and year from all three datasets and used for statistical analysis and graphical presentation. Except for the first dataset, collected 1936–1961 (Russell 1962), we excluded phenology data from the greater Edmonton area. Edmonton's human population has grown at an exponential rate to over one million from 85,000 at the beginning of this research (Statistics Canada 2010). It is therefore possible that urban heat island effects on temperature may confound data on climate change trends (e.g. Rötzer et al. 2000) .

The three observation programs, those of Russell (1962), Bird (1983), and Beaubien (Beaubien and Johnson 1994, Beaubien and Freeland 2000) included the same four woody and three herbaceous (non-woody) plant species (figure 2-2). The first species to bloom is the prairie crocus (*Anemone patens* L.), which is found in grasslands throughout the northern hemisphere and blooms soon after snow-melt. Usually blooming within two days of the prairie crocus is the trembling aspen (*Populus tremuloides* Michx.), one of the most common and widely-distributed tree species in North America. It is the first tree in Alberta to shed pollen and produce leaves in spring. About 25 days later, the saskatoon or serviceberry (*Amelanchier alnifolia* Nutt.), blooms. The saskatoon is a widespread tall woody shrub with edible berries that were the most important plant food for the prairie Blackfoot First Nations. The remaining four species follow in approximately eight-day intervals, starting with the choke cherry (*Prunus virginiana* L.), a tall woody shrub that is also widespread throughout North America. The wolf willow or silverberry (*Elaeagnus commutata* Bernh. ex Rydb.) is a nitrogen-fixing, medium-sized shrub with a short, well-defined bloom period and an overpowering smell that aids correct identification. The northern bedstraw (*Galium boreale* L.) is another widely-distributed and easily-identified herbaceous species. The last species in this sequence is the yarrow (*Achillea* *millefolium* L.), perhaps one of the best known and most widely-distributed herbaceous species in the world. In this section, we followed the scientific nomenclature of Moss and Packer (1983).

2.3 Climate and phenology trends

We used daily minimum, maximum, and mean temperature data obtained from the Adjusted Historical Canadian Climate Database (AHCCD 2009) to analyze climate trends. This database includes four weather stations with long-term records for the study area (figure 2-1): Edmonton international airport (ID #3012205) which is well outside the city of Edmonton, Lacombe (ID #3023722), Calmar (ID #3011120), and Coronation (ID #3011887). To visualize temperature trends and compare station records, we also calculated mean monthly minimum, maximum, and mean temperature values for February to June from daily data. In addition we generated interpolated monthly data according to Mbogga et al. (2009) for the central parkland ecoregion. Interpolated climate data as well as station data suggest that the central parkland ecoregion is climatically very homogenous. Mean monthly February, March, and April temperatures for the 1961 to 1990 normal period differed by less than 1°C among any pair of the four weather stations and among grid cells of the interpolated surface. The average correlation coefficient among pairs of stations was 0.97 for mean monthly temperatures from February through June. Because of the climatic homogeneity of the study area, we used mean climate values from the four weather stations for subsequent analysis, which matches the data preparation of phenology observations as regional averages for the central parkland.

We observed a substantial warming trend between 1936 and 2006 that was most pronounced in late winter and early spring (figure 2-3). For the 70-year period of this research, the slope of a linear regression equates to a 5.3°C increase in the mean February temperature, a 2.7°C increase in the mean March temperature, and a 1.8°C increase in the mean April temperature. These trends were even more pronounced in mean monthly minimum temperatures (6.0°C, 3.9°C, and 2.2°C, for February, March, and April respectively), whereas the mean maximum temperature changes over the study period were 4.5°, 1.5°, and 1.5°C. A Mann-Kendall test for identifying trends in time series data following the method of Hipel and McLeod (1994) reveals that warming trends for minimum monthly temperatures from February to April were statistically significant at $\alpha = 0.05$ (table 2-1).

The annual sequence of species' first bloom dates was fairly consistent between years (figure 2-4a). The plants responded by blooming earlier in spring, with the most pronounced changes in the earliest species (*A. patens* and *P. tremuloides*). These species' flowering dates advanced by approximately two weeks, whereas the later-blooming species' flowering dates advanced between zero and six days over the study period. A Mann-Kendall test also confirmed the advanced blooming in the earliest-blooming species as statistically significant (table 2-2). This result corresponds to the observed temperature changes, with considerable warming in late winter but minimal warming in late spring.

Trends toward an earlier onset of spring phenology in the Northern Hemisphere are well documented in the literature. In a meta-analysis for the Northern Hemisphere, Root et al. (2003) revealed an average 3-day advance per decade in tree phenology, with somewhat more pronounced trends at higher latitudes. For Western Europe, Menzel and colleagues (2006) and Schleip and colleagues (2009) analyzed phenology time series of at least 30 years between 1955 and 2000. They found that changes in spring phenology of plants were most pronounced in central and western maritime Europe, advancing around 3.5 days per decade. These changes appear to be larger than our observations for our earliest blooming species (which advanced approximately 2 days per decade). However, the difference arises mainly from the observation period. For example, in a long-term study of UK plant communities, Amano and colleagues (2010) found approximately the same 3.5 days per decade rate of change as Menzel and colleagues (2006) over the last 30 years. Conversely, the rate of change over the 70 years corresponding to our study only shows an advance of approximately one day per decade for data from Amano and colleagues (2010) because most of the observed warming at their study site occurred over the last 30 years. Our observation of a total advance of 14 days for *A. patens* and *P. tremuloides* over a 70 year period appears to be on the high end of changes observed in the Northern Hemisphere.

2.4 Thermal time models of spring development

Thermal time models use daily temperature data to predict the timing of bud break or flowering. Daily temperatures are, however, not directly used as predictor variables. Instead, daily temperature values are integrated over time by adding daily temperature measurements. The derived predictor variable for bud break or flowering is the date where the sum reaches a certain value (the required heat sum). Réaumur (1735) was the first to establish the principle of thermal time and the concept of degree days as a predictor for plant development. Degree-days are calculated as the sum of daily average temperature values from a chosen start date (often arbitrarily set as 1 January) and a threshold value (often 0 to 5 ºC for early spring-blooming species). This summation continues up to the day of a phenology event, yielding a required heat sum for the observed event.

This classical thermal time model has been modified in various ways to account for non-linearity of the physiological response to temperature - for a review, see Bonhomme (2000). Other modifications include accounting for chilling requirements of plants before temperature accumulation begins, or for additional environmental factors – for a review see Chuine et al. (2003). Nevertheless, the simple linear model has proven to be surprisingly accurate, often having just one variable parameter: minimum temperature threshold. This parameter bounds the lower end of the temperature range that is assumed to be approximately linearly correlated to a spring physiological response (Bonhomme 2000). Sometimes, different start dates of heat sum accumulation other than 1 January are tested to account approximately for dormancy release or photoperiod effects (e.g.Wielgolaski 1999). Complex mechanistic or statistical models often yield only minor improvements, if any, over the classical thermal time model, particularly for studies that are not carried out in controlled environments (e.g. Hannerz (1999), Schaber and Badeck (2003), Linkosalo et al. (2006) .

In figure 2-4b and table 2-3, we show the results from a classical thermal time model applied to our data. The development of a thermal time model involves the selection of a base temperature for degree day calculations, for example 0°C. The next step is to calculate the required heatsum for an observed phenology event to occur. This required heatsum is a mean value based on the phenology events of a species observed over multiple years that can be estimated with a standard error (HS ±SE in table 2-3). With a species-specific required heatsum value, we can now use daily temperature data to predict a bloom time for each year (figure 2-4b). The correlation between observed bloom dates in each year (figure 2-4a) and bloom date predicted by the thermal time model (figure 2-4b) serves as measure of model fit. The model fit may be improved by modifications of base temperatures or start dates.

We tested a wide range of base temperatures for degree day calculations from –10 to +10°C in one degree intervals. Further, we tested multiple start dates for temperature accumulation (1 January, 1 March, and 31 March), to account for possible unmet chilling requirements. The best thermal time model, i.e. the one with the highest correlation between observed and predicted flowering dates, was obtained with threshold values between –3 and 3°C (table 2-3, bold correlation coefficients). This is a fairly typical result for northern temperate and boreal plant species, which usually have optimal threshold parameters between 0 and 5°C (e.g. White 1995, Hannerz 1999). As was expected for a northern environment, later start dates did not improve the correlations, suggesting that species' chilling requirements were met before winter. We therefore report only statistics for a start date of 1 January in table 2-3.

Correlation coefficients are a good measure to assess statistical error, but they do not detect statistical bias (systematic over- or under-prediction). We therefore validated the thermal time model using a second statistical measure, mean absolute error (MAE). MAE is calculated as the absolute difference between observed and predicted bloom dates. We carried out an independent cross-validation based on a temporal split of the temperature and phenology data. The first two thirds (1936-1986, with approximately 40 years of data) were used for the development of the thermal time model, and the last third, (1987-2006) was used for model validation.

Generally, the classical thermal time model appears to be very accurate in predicting mean bloom dates of species in the central parkland (table 2-3). The MAE values in predicting bloom time in the independent cross-validation ranged from ±1.6 to ±4.5 days. The species with the largest MAE values were the earliest blooming species, *A. patens* and *P. tremuloides*. For these species, the predictions were biased, under-predicting the rate of change in bloom time (compare figure 2-4a vs. 2-4b).

2.5 Observed versus predicted phenology trends

In an attempt to explain the discrepancy between the observed and predicted trends in *A. patens* and *P. tremuloides*, we used a multiple regression approach to incorporate other climatic and environmental factors (equation 1 in Chuine et al. 2003). The environmental factors we tested include the amount of winter precipitation that fell as snow, the depth of snow pack at the end of February and March, and several dryness indices. We also checked for effects of chilling requirements in the previous fall, with chilling degree days calculated between the upper and lower thresholds of 0°C and 5°C, and 2°C and 8°C according to Linkosalo and colleagues (2006). None of these additional factors could account for a significant portion of the variance that was not already explained by the thermal time model (data not shown). A non-linear, Q_{10}-based thermal time model according to Bonhomme (2000) yielded model accuracies for all species (measured as r^2 between observed and predicted events, and as SE of heat sum) that were similar to previous results (figure 2-4b). However, they actually increased the discrepancy between observed and predicted temporal trends for the early-blooming species by a small amount (data not shown).

A possible remaining explanation for this unexplained variation is that spring phenology is not only a function of mean daily temperatures; it is also influenced by the amplitude of diurnal temperature variations. Karl and colleagues (1993) were the first to demonstrate that global minimum temperature increased faster than maximum temperature, resulting in a significant decrease of diurnal temperature variation, which was subsequently confirmed by Easterling and colleagues (1997). This differential warming pattern in minimum and maximum temperatures clearly applies to our study area as well, where the minimum night temperatures in March increased more than twice as fast as the daily maximum temperatures (figure 2-3, table 2-1). We therefore hypothesize that the increase of the minimum night temperature relative to the mean daily temperatures used in the heat sum model results in a more rapid heat sum accumulation. Although heat sum accumulation based on minimum night temperatures is not biologically reasonable as it does not incorporate daytime temperature exposure, we explored this option as well. The result is a reduced model fit (r=0.79 for *P. tremuloides)*, but the flowering advance over time is predicted more accurately (14 days observed versus 13 days predicted over the study period). It makes adaptational sense that minimum temperature values (which could represent damaging frost events) modulate daytime thermal time accumulation to control spring development. This would allow plants to fine-tune spring development for microsites with different diurnal temperature variation but may also increase the exposure of *P. tremuloides* and *A. patens* to late spring frosts under climate change.

2.6 Exposure to late spring frost

Late spring frosts of -10°C occurred earlier in the year, at a rate of 0.7 days/per decade, and very severe spring frosts of -20°C occurred earlier at a rate of 1.1 days/per decade over the study period (data not shown). This is a considerably slower rate than the advance of bloom time for early species, which occurred at a rate of approximately 2 days/decade (figure 2-4a). This discrepancy raises the question whether early blooming species might be exposed to increased risks of late spring frosts because of climate change.

To answer this question, we compared the incidence of late spring frost events with the timing of first bloom. In figure 2-5, we show the variance of bloom times observed across a population sample of *Anemone patens* for different years by means of a special form of boxplot, the so-called violin plot, which reveals the frequency of bloom observations for different dates. This plot quantifies bloom dates of the sampled population (width of violin plot indicates frequency) as well as the latest dates of spring frost events ranging from 0° to -20°C (represented by the gradient of gray). To give an example, in 1994 and 1995 there were frost events of -20°C as late as April 30 and 28 respectively (day 120 and 118). That means that virtually all reported flowering individuals were exposed to these extreme frost events. As a contrasting example, in 2000 we had a -12°C event that occurred on April 14 (day 104). This affected only the early-blooming portion of the population. Most individuals bloomed after that late frost event and were only exposed to -4°C frosts that occurred as late as day 133 (May 13). In figure 2-5, trends toward an earlier bloom would be represented by violin plots being located higher on the left than on the right side. Higher frost exposure experienced by blooming populations would be visible by darker colours towards the right side. Note that we have population-level information from many observers of the PlantWatch Alberta network only since 1987. Before that date, we assume a normal distribution around a known annual average reported by Russell (1962) and Bird (1983).

In the case of *A. patens,* we can see a slightly increased exposure of blooming populations to frost events over time, with overall darker shades toward the right side of figure 2-5. To test whether this trend is statistically significant, we cannot directly use the distributions shown in figure 2-5, because we lack population-level data before 1987. Instead, we analyzed trends in the value of the coldest frost event following the average bloom times shown in figure 2-4a for each year (table 2-4; later blooming species that were not exposed to frost were excluded). For example, *A. patens* individuals with an average bloom time were exposed to colder spring frost events, at a rate of -0.57°C per decade. This means that frost events to which blooming plants are exposed, are on average 4°C colder at the end than at the beginning of the study period. This trend was not significant for any other species at an α level of 0.05. However, two other early-blooming species showed similar trends toward increased exposure to frost, and trends of this magnitude or larger would arise by random chance only once in 19 times (*P. tremuloides*) or once in 16 times (*Amelanchier alnifolia*).

This paradoxical result of increased frost risk with climate warming agrees with phenology studies in the Colorado mountains (Inouye 2008). But Scheifinger and colleagues (2003) observed that frost risk in central Europe generally decreased, because the retreat of late frosts outpaced the advance of spring development. However, the low heat sum requirements of species from environments with short growing seasons results in a finely-tuned adaptive balance between avoiding spring frost and using the available growing season (Li et al. 2010). Earlier snowmelt due to higher temperatures or lower winter precipitation may affect this balance in high-elevation environments (Inouye 2008). In our study, at relatively high latitude, we excluded snow as a factor that can explain the unexpectedly sensitive phenological response of *A. patens* and *P. tremuloides* to warming trends. Instead, changes in diurnal temperature fluctuations may be responsible for a faster advance in bloom dates than can be explained by standard thermal time models.

While this explanation is speculative, it could guide future experimental research toward the development of improved thermal time models that take diurnal temperature fluctuations into account. Regardless of whether diurnal temperature variations are the ultimate cause of the discrepancy between observed and predicted trends, our results suggest that projections of phenology response into the future, although they are important (e.g. Leinonen and Kramer 2002), should be made with caution. Models that explain interannual variation of plant response very well over a limited observation period may not always provide reliable long-term projections. In the case of *P. tremuloides* and *A. patens*, it appears that we would under-predict climate change response by 23% and 44% respectively, with a standard thermal time model.

2.7 Conclusions

In this study, we documented considerable advances in phenology over time that were driven by what we perceive as astonishing warming trends in spring temperature. Particularly in March, we also found large changes in diurnal temperature fluctuations (average daily minimum temperatures increased 2.7 times faster than daily maximum temperatures in this month). The phenology response of two early-blooming species, *A. patens* and *P. tremuloides,* appears to be unexpectedly sensitive to these temperature changes. Their bloom times changed twice as fast as did the frost events, thus shifting their bloom period closer to the receding winter and increasing the danger of damage from late-spring frost.

The database we analyzed was assembled as a collaborative effort among university biologists, government researchers, and over 650 members of the general public. This effort has both harnessed the energy of concerned citizens, and provided them with biological insights and a raised awareness of climate change issues in Alberta. Besides documenting biological response to global climate change, citizen scientists' contributions are invaluable for the validation of remote sensing data and the calibration of carbon uptake models in terrestrial ecosystems (Badeck et al. 2004). In conclusion, we would like to encourage interested readers to join local phenological networks that make this research possible. Links to local networks can be found at *www.plantwatch.ca* for Canada, and *www.usanpn.org* for the United States.

Table 2-1 Mann-Kendall test statistics for time series trends in minimum, maximum, and mean monthly temperature (shown in figure 2-3) over the period 1936-2006. P-values indicating a significant trend over time at α = .05 are highlighted in bold.

Temperature		°C/decade	†	Prob(>†)
Average	February	0.75	0.28	**0.0003**
	March	0.39	0.15	**0.0365**
	April	0.26	0.12	0.0756
	May	0.02	0.04	0.3010
Minimum	February	0.86	0.31	**0.0001**
	March	0.56	0.21	**0.0052**
	April	0.31	0.18	**0.0157**
	May	0.05	0.10	0.1275
Maximum	February	0.64	0.28	**0.0004**
	March	0.21	0.07	0.1854
	April	0.21	0.07	0.1928
	May	0.00	0.04	0.5874

Table 2-2 Mann-Kendall test statistics for time series trends in first bloom dates for seven plant species over the period 1936-2006, expressed in number of days per decade shift to earlier bloom time (shown in figure 2-4a). P-values indicating a significant trend over time at $\alpha = .05$ are highlighted in bold.

First bloom of	Days/decade	τ	Prob($<\tau$)
Anemone patens	-2.1	-0.26	**0.0039**
Populus tremuloides	-2.0	-0.29	**0.0008**
Amelanchier alnifolia	0.0	0.03	0.6181
Prunus virginiana	-0.6	-0.09	0.1759
Elaeagnus commutata	-0.7	-0.16	0.0735
Galium boreale	-0.4	-0.03	0.3735
Achillea millefolium	-0.9	-0.09	0.1673

Table 2-3 Correlation between flowering date and thermal time calculated for different base temperature values for heat sum accumulation. The threshold value for the best model (highest correlation) is shown in bold. The heatsum for the best model (HS) is provided with a standard error (SE) of the estimate. The heat sum for a threshold of 0°C (HS_0) is provided for comparison of thermal time requirements across species. Results from an independent cross validation are reported as mean absolute error (MAE) of observed versus predicted bloom time.

Species	Years	Heatsum			Correlation coefficients for base temperatures							MAE (days)
		HS_0	HS	SE	-3°C	-2°C	-1°C	0°C	1°C	2°C	3°C	
Anemone patens	50	94	187	9.6	**0.81**	0.80	0.79	0.78	0.75	0.72	0.68	3.9
Populus tremuloides	60	103	202	6.4	**0.90**	0.89	0.88	0.88	0.86	0.84	0.81	4.5
Amelanchier alnifolia	60	303	172	3.1	0.84	0.86	0.87	0.89	0.90	0.91	**0.92**	1.6
Prunus virginiana	57	419	258	3.8	0.84	0.86	0.87	0.89	0.90	0.90	**0.91**	2.4
Elaeagnus commutata	44	511	385	7.0	0.75	0.76	0.78	0.79	0.80	**0.81**	0.81	3.5
Galium boreale	58	690	467	6.3	0.70	0.72	0.74	0.75	0.75	0.76	**0.77**	2.1
Achillea millefolium	52	782	696	8.9	0.69	0.71	0.72	0.73	**0.74**	0.73	0.72	2.2

Table 2-4 Mann-Kendall test statistics for time series trends (over the period 1936-2006) in the value of the coldest frost event following average bloom time, expressed in °C change per decade. P-values significant at $\alpha = .05$ are highlighted in bold.

Frost exposure for	°C/decade	τ	Prob($<\tau$)
Anemone patens	-0.57	-0.20	**0.0231**
Populus tremuloides	-0.44	-0.15	0.0521
Amelanchier alnifolia	-0.13	-0.06	0.0671
Prunus virginiana	-0.01	0.01	0.4909

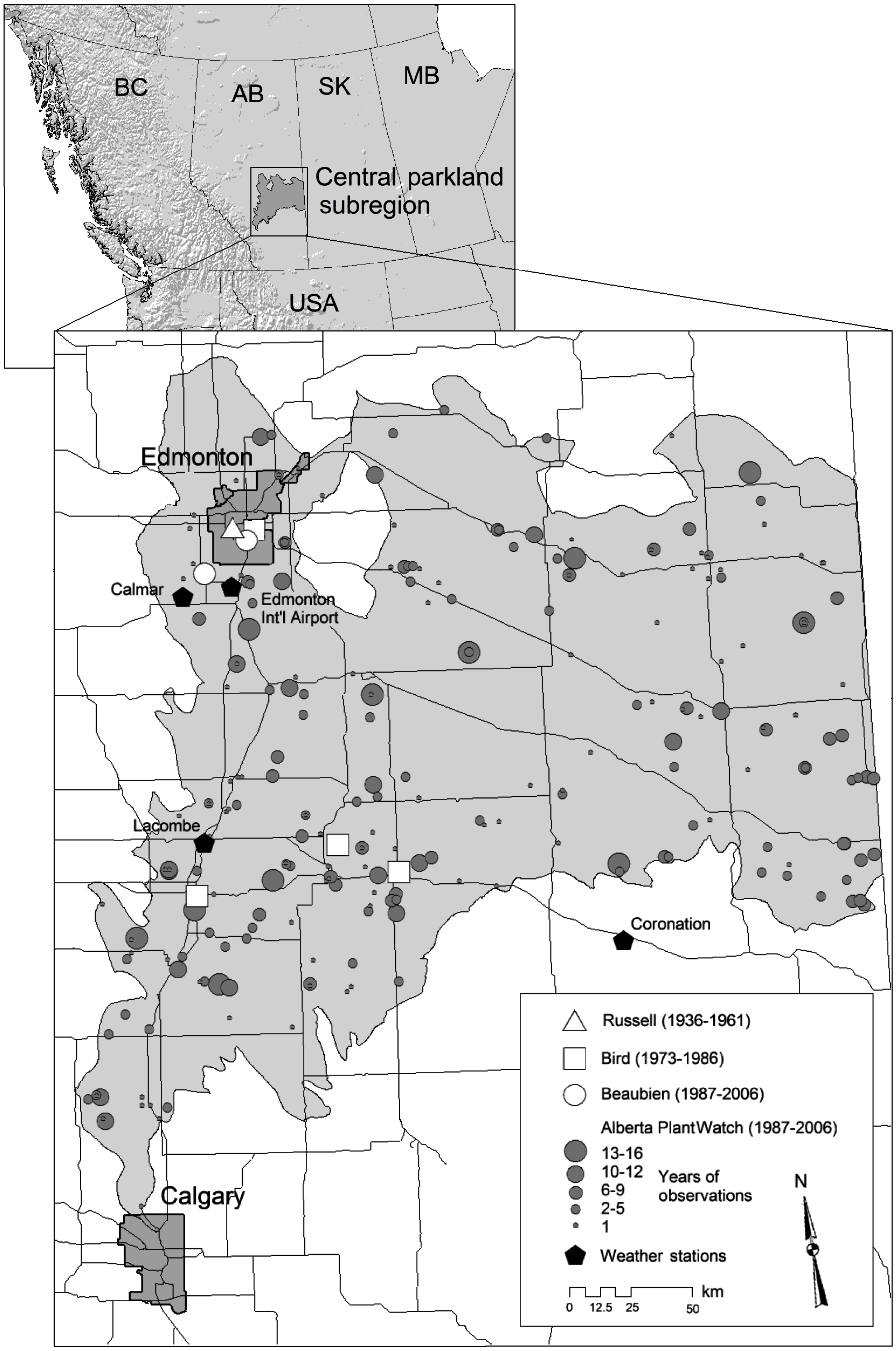

Figure 2-1 Central parkland study in Alberta, western Canada. The figure indicates the location of long-term weather stations and locations of phenology observations. The white symbols indicate long-term observations. For the Alberta PlantWatch network, the size of the circles indicates the length of data collection by a volunteer.

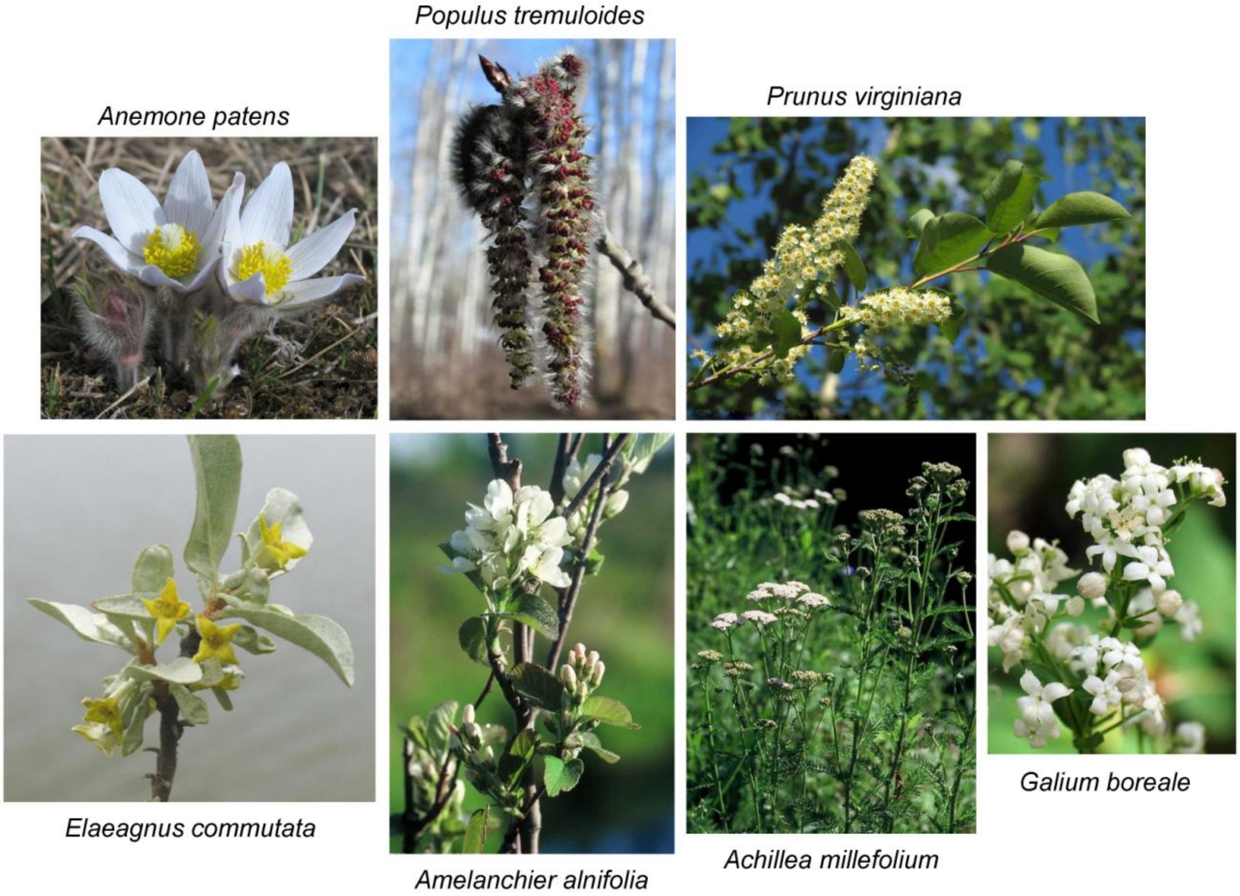

Figure 2-2 Species included in the study were prairie crocus (*Anemone patens* L.), trembling aspen (*Populus tremuloides* Michx.), choke cherry (*Prunus virginiana* L.), wolf willow or silverberry (*Elaeagnus commutata* Bernh. ex Rydb.), saskatoon or serviceberry (*Amelanchier alnifolia* Nutt.), yarrow (*Achillea millefolium* L.), and northern bedstraw (*Galium boreale* L.). Photos by Linda Kershaw.

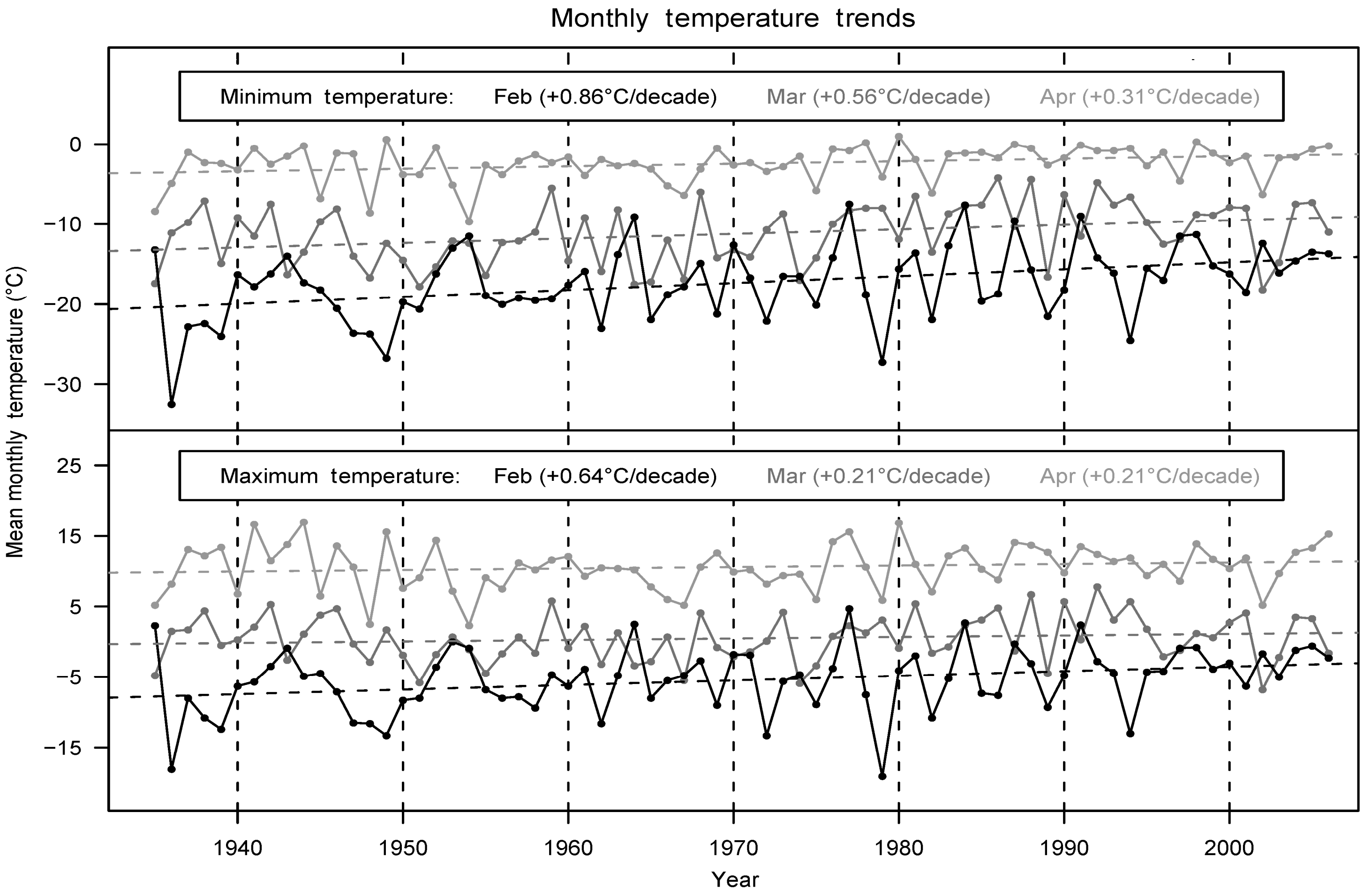

Figure 2-3 Temperature trends for the central parkland study area for the mean monthly minimum temperature (in degrees Celsius), and the mean monthly maximum temperature.

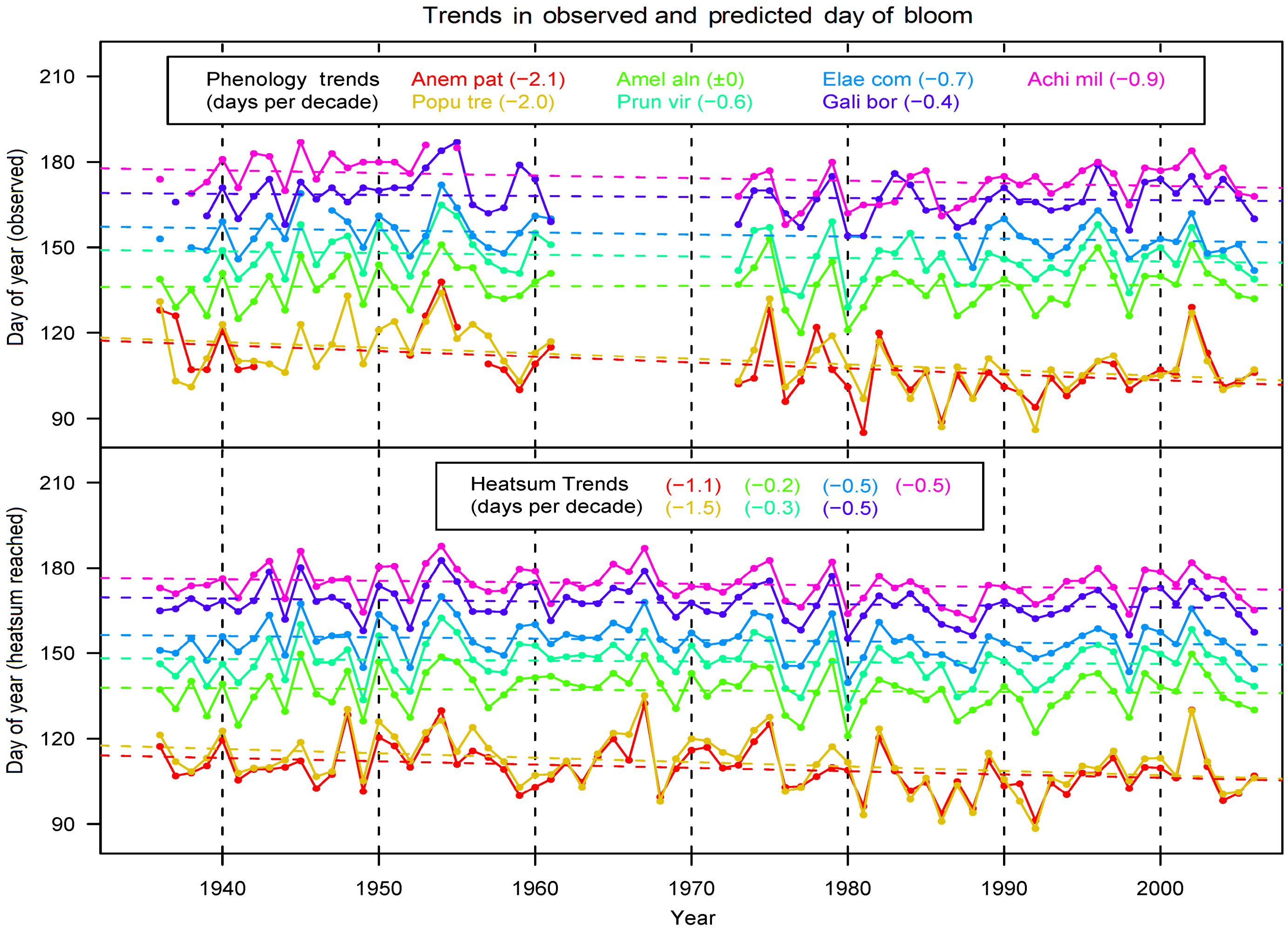

Figure 2-4 Trends in observations of first bloom for seven species. Species names are abbreviated using the first four letters of the genus and the first three letters of the species name provided in figure 2-2. The lower panel indicates the predicted day of first bloom from a thermal time model (the best model highlighted in bold in table 2-3).

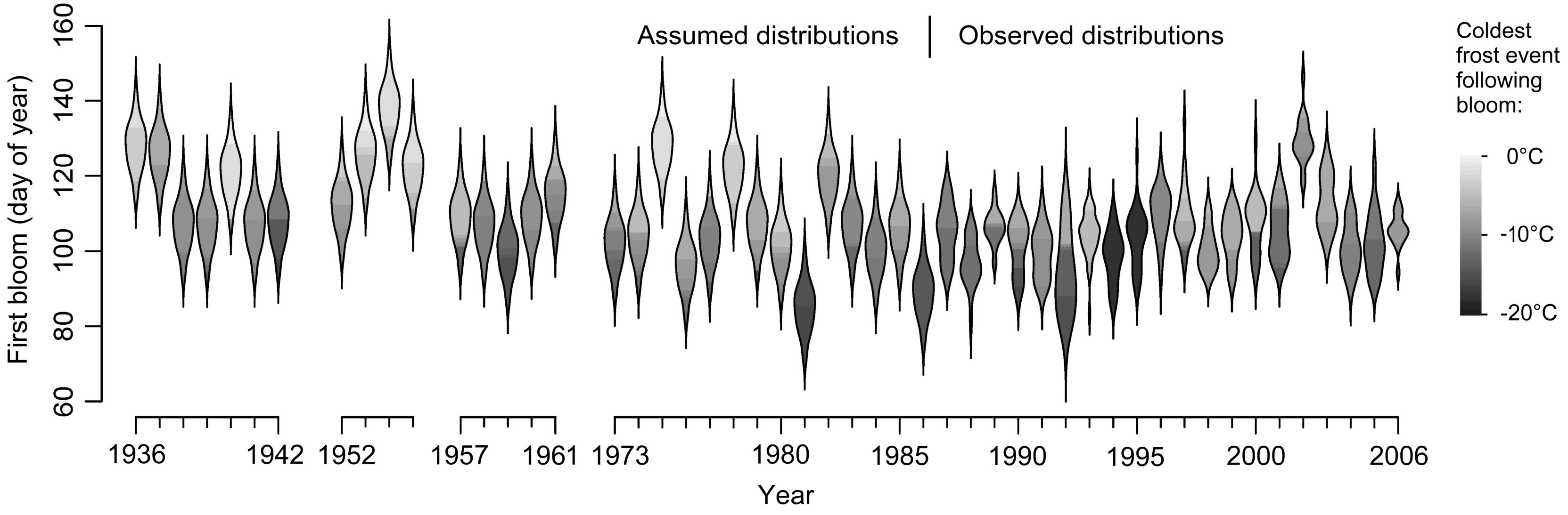

Figure 2-5 The distribution of the day of the year when flowers appear in *Anemone patens* individuals. The width of each annual "violin" plot indicates the frequency of reported observations for different dates. The grey-scale (gradient) indicates the severity of frost events to which blooming individuals were exposed, with the lighter part of the gradient representing less severe frost events. We have population-level data available only since 1987. Before that date, we assume a normal distribution (which is used only for visualization in this figure).

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Chapter 3 - Urban Heat Island Effects Partially Explain Earlier Blooming of Plants in Edmonton, Canada

Summary

An important criticism by climate change skeptics is that much of the observed warming signal is an artifact of the increasing heat island effect of growing cities where weather stations are frequently located. As heat island effects of urban centers intensify over time due to population and economic growth they are confounded with general climate warming trends. Here, we quantify heat island effects over a period of 70 years based on weather station and phenology data from urban and rural areas around Edmonton, a city at 53°N latitude. Due to the high spatial density of the observer network, we were able to, for the first time, create a continuous heat island map through interpolation from phenology data. Further, we documented an increasing heat island effect over the period 1931–2006 in both weather station data and plant phenology response. Across all seven plant species, the advance in phenology observed in Edmonton was 2.1 days (±0.9 SE) greater than in the surrounding rural areas, with the heat island effect accounting for one third of the total warming signal.

3.1 Introduction

There has been a long-standing discussion among climatologists whether urban heat island effects explain a significant proportion of the observed global warming signal (e.g. Parker 2004). Many factors influence the urban heat island. First, the impact on local climate is influenced by the size of the city. As the intensity of the urban heat island is proportional to the log of the urban population (Oke 1987), population statistics are most often used to estimate changes in heat island (Landsberg 1981, Barry and Chorley 2010). Next, the change of land cover from vegetation to hardened surfaces (concrete, asphalt, brick, etc.) causes at least two reductions in summer cooling from evapotranspiration: loss of soil with its water storing capacity and loss of vegetation with evaporative cooling potential (Oke 1987). In addition, the hardened material has a high thermal mass and is slow to cool at night, releasing heat into the atmosphere. In north temperate North America, major urban-rural temperature differences are generally seen in the winter season, due to emissions from burning fossil fuels for heating and transport (Landsberg 1981, Hinkel and Nelson 2007). The presence of wind also has short-term effects on the heat island; greatest urban-rural temperature differences are found on calm nights, but this effect diminishes on windy nights (Landsberg 1981).

The timing of spring blooming and leafout of perennial plants in temperate climates is driven mainly by the rate of increasing temperature after mid winter (Rathcke and Lacey 1985). After a warmer than usual winter and spring, plants bloom earlier than average. Studies of shifts in plant phenology in the northern hemisphere generally show trends towards earlier bloom and leafout times (Menzel et al. 2006, Bertin 2008), and in Europe higher population density was associated with earlier plant response timing (Estrella et al. 2009). The geographic extent of the urban influence on plant response can be considerable. In one remote sensing study, urban land cover was second in importance after elevation as a driver of landscape phenology, affecting the start of the growing season up to 32 km from the centres of large cities (Elmore et al. 2012). Another study based on satellite data showed that earlier urban budburst, compared to surrounding rural areas, was found in 75% of temperate cities examined, but only in 33% of tropical cities (Gazal et al. 2008).

Phenology observations done on the ground in North America, Europe and China have shown that flowering in spring-blooming plants starts earlier in cities than in rural surroundings (Neil and Wu 2006). But compared to North American cities, European cities have smaller urban-rural temperature differences, perhaps due to a greater density of the rural population, greater extent of forest clearing and generally lower heights of buildings in Europe (Oke 1987, Barry and Chorley 2010). A comparison of 10 urban-rural areas in Europe found that city spring bloom times for one herbaceous and three woody plant species were four days earlier than rural bloom times, over the period 1951-1995 (Rötzer et al. 2000). But a study of three German cities (1980 to 2009) did not find significant differences in phenology due to urbanization (Jochner et al. 2012). In North America, data are limited on the effects of urban heat island on plant phenology. Studies have largely focused on herbarium specimens solely from urban areas (Primack et al. 2004, Houle 2007, Neil et al. 2010), were limited to a single non-native plant species (Ziska et al. 2003, Lavoie and Lachance 2006), or relied on satellite imagery for evidence of change (Zhang et al. 2004, Gazal et al. 2008).

In Europe and Asia, remote sensing data showed that mean annual city temperatures were about 0.8°C warmer than nearby rural areas, whereas in the USA city temperatures were 1-3 °C warmer (Zhang et al. 2004). The effects of the urban heat island on plant phenology are also smaller in Europe and Asia than in North America (Zhang et al. 2004). In the Alaskan community of Barrow (71° N latitude), the urban area was 2.2 °C warmer than the rural area, based on spatial averages for the period 1 December 2001 to 31 March 2002 (Hinkel et al. 2003). Expanding temperate urban centres have similar temperature patterns to those caused by general climate warming, where minimum temperatures are increasing faster than maximum temperatures, thus reducing the daily temperature range (Easterling et al. 1997). Mimet et al. (2009) took measurements along a gradient from outside the city to city centre (Rennes in France) and found an increase in minimum temperature accompanied by a trend to earlier plant phases. This reduction in diurnal temperature variability increases the rate of temperature accumulation in heat sum calculations and could be the reason for an observed increase in the sensitivity of phenological response over 70 years in central Alberta (Beaubien and Hamann 2011a).

The spatial pattern of temperatures in cities influences plant response. Another study along an urban-rural gradient showed that the allergenic ragweed (*Ambrosia artemisiifolia*) had earlier flowering and increased pollen production closer to the city centre of Baltimore, Maryland (Ziska et al. 2003). Secondly, the pace of increasing spring temperatures can also affect urban-rural phenology differences.

Periods of high temperature in spring can cause synchronous blooming in urban and rural areas, whereas cool periods may lead to larger urban-rural differences in bloom times (Jochner et al. 2011). Lastly, urban heat island effects on phenology may vary according to the plant species or phenophase (growth stage) observed. The study by Roetzer et al. (2000) indicated that the 'start of season' plants (those that flower earliest in spring) react more strongly to temperature, showing a bigger heat island effect, i.e. more difference between urban and rural bloom times.

In 10 central European cities, spring phenophases for four early-blooming plants showed larger city trends to earlier onset for more recent years (1980 to 1995) (Rötzer et al. 2000). The analysis of trends for the period from 1951 to 1995 showed tendencies towards earlier flowering in all regions, but only 22% were significant at the 5% level. However the trend to earlier bloom was bigger in rural areas, perhaps due to differences in rates of urbanisation. In this study the rural stations were not far from city centres. Few studies have been done on the effect of urban heat islands on phenology in North America. In eastern Canada, Lavoie and Lachance (2006) used 216 herbarium specimens of the non-native *Tussilago farfara* (coltsfoot) from southern Quebec and found that in the urban centres of Montreal and Quebec, there were major shifts of 15-31 days to earlier bloom since the early 20th century. No trend was found for rural areas. In light of this large urban-rural difference it is odd that this European species was shown to be relatively unresponsive to temperature in a study in Finland: flowering dates had a correlation of only 0.30 with the best heat sum, while correlations of other species were 0.66–0.90 (Heikinheimo and Lappalainen 1997). Research in central Europe has been hampered by lack of adequate urban phenology data (Jochner et al.

2011), or in much of Europe, lack of truly rural data due to a generally urbanized landscape. Jeong et al. (2011) report on trends in spring temperatures and flowering times for four shrubs in nine cities of South Korea, 1954-2004. Urban warming resulted in an advance of many days to many weeks in bloom dates, and the size of this shift to earlier blooming was related to the degree of urbanization. But information on changes in rural areas, for comparison, is not presented.

In the rural area surrounding Edmonton, Alberta (the study area for this paper), there is substantive evidence of climate warming. Minimum February temperatures in this Central Parkland ecozone increased by 6 °C over the 70 years 1936-2006 (Beaubien and Hamann 2011a). While it is not the subject of this study, we concur with Parker (2004) and Wickham et al. (2011) that overall climate warming is not a consequence of urban development. There is a need to understand the difference between temperatures and the biotic response both inside and outside cities, and few studies have quantified heat island effects with rigorous rural-urban comparisons. In this article we contribute what could be an extreme case of urban heat island effect on plant response in spring, due to a quickly expanding city, a cool boreal climate, and considerable trends to early blooming. Our dataset is unique in having data on many plant species from both urban and rural sites in western Canada. We ask: what is the contribution of the urban heat island to the climate warming signal?

3.2 Methods

3.2.1 Study area and phenology observations

Our study area included the city of Edmonton, Alberta, Canada (53.54° N latitude, 113.49° W longitude, altitude 660 m) and surroundings, an area of continental climate with warm summers and dry cold winters (Figure 3-1). Using plant phenology records from Alberta PlantWatch, we selected species with abundant rural and urban data. For additional information on this program and database see Environment Canada 2009, Beaubien and Hamann 2011a, Beaubien and Hamann 2011b, and Beaubien 2012. Alberta PlantWatch data for 1987-2006 consisted of over 47000 observations of bloom and leafing dates of plants, gathered by 650 observers.

We selected the phenophase ‘first bloom’ for analysis, as it had more abundant data. For the period 1987 to 2001, first bloom was defined as “10% of flower buds open”. After 2001 the definition became “first flowers open in three different places on a woody shrub or tree”, or “first flowers open in a patch of herbaceous plants”. For the tree *Populus tremuloides* the updated definition was “the date when the catkins on the observed male tree first start shedding pollen in 3 different places”. We added 1060 records from data gathered by E. Beaubien for plants in the city and at the rural Devonian Botanic Garden, 10 km west of the southwest corner of the city boundary. In this dataset, ‘first bloom’ was defined as “1-25% of flower buds now open”. To reflect conditions in the years when Edmonton was a smaller city, we used historic first bloom data (one date per species per year) for 1936 to 1961, from a study done by Agriculture Canada (Russell 1962). These Edmonton observations were largely done on the University of Alberta campus close to the centre of the city. The following species were included in this study: Prairie crocus (*Anemone patens* L.), aspen poplar (*Populus tremuloides* (Michx.)), saskatoon (*Amelanchier alnifolia* Nutt.), chokecherry (*Prunus virginiana* L.), wolf willow (*Elaeagnus commutata* Bernh. ex Rydb.), northern bedstraw (*Galium boreale* L.) and yarrow (*Achillea millefolium* L.), following the nomenclature of Moss and Packer (1983).

3.2.2 Climate data

To examine changes in winter- spring temperatures, we used weather records for daily temperatures for two weather stations: the city of Edmonton and the small rural town of Calmar 20 km southwest of Edmonton's city boundary (Figure 3-1). These records were obtained from the Adjusted Historical Canadian Climate Database (AHCCD 2009), which included weather stations with long-term records for the study area. For the urban data we merged two long term data sets: Edmonton (ID #3012195) with data from 1880 to 1943, and Edmonton city centre (ID #3012208) with data from 1938 to 2005. For a rural station we chose the small town of Calmar, (ID #3011120), with data from 1915 to 2007 (Figure 3-1). Calmar had a population of only 2000 people in 2006. From the daily data, we calculated the mean monthly temperatures for the winter months (January to March) and spring (April to June) and plotted differences between city and rural monthly temperatures. Required chilling (exposure to low temperatures needed before woody plants can respond to spring warming) is complete in early winter in this area (Beaubien and Hamann 2011a) so fall temperatures were not included in the analysis.

3.2.3 Statistical Analysis

To test for significant trends in the magnitude of the urban heat island effect over time, we calculated temperature differences between the urban Edmonton and rural Calmar stations over eight decades, and separately analyzed data for the months of January to June. We used linear regression over time to identify significant trends over time, implemented with the *cor.test* and *lm* functions of the R programming environment (R Development Core Team 2008).

Differences between rural and urban phenology observations were based exclusively on phenology data representing the first bloom phase. Urban versus rural effects were tested with a mixed model implemented with PROC MIXED of the SAS statistical software package (SAS Institute 2008). Year of observation was considered a random effect, and the urban versus rural treatment was considered a fixed effect. Treatment means and standard errors were estimated with the LSMEANS option, and plots of urban and rural means over time with standard errors were generated using the *ggplot2* package for the R programming environment (R Development Core Team 2008).

To generate interpolated surfaces of bloom dates, we included all available phenology observations (first bloom, mid-bloom and full-bloom). We then applied a mixed model as described above to account for effects of year (random effect) and observed bloom stage (fixed effect), while the urban versus rural effect was excluded from the model. The residuals of this model can therefore be interpreted as unexplained deviation from the average bloom date for a 225×225 km study area centered on Edmonton, Alberta. The residuals were plotted on a map, where the mean residual value was shown if multi-year data were available for a single location. The residuals were then interpolated using ordinary kriging with a spherical semivariogram model, implemented with ArcGIS 9.3 (ESRI 2011).

3.3 Results and discussion

3.3.1 Urban growth as a measure of changing heat island

The growth of Edmonton is shown in Table 3-1, where population statistics for 1901 to 2011 are given. The category “greater Edmonton area” refers to the “census metropolitan area”, a grouping of census subdivisions comprising the large urban area and surrounding urban fringes. The greater Edmonton area population continues to increase very rapidly: with an additional 12% (2006 to 2011), it is the second-fastest pace of growth of any Canadian metropolitan area. The values for the periods of the historic Agriculture Canada plant phenology data (1936-1961) as well as the more recent Alberta PlantWatch data set (1987-2006) are given for comparison.

3.3.2 Heat island effects as seen in weather data

Winter weather data for Edmonton versus Calmar showed that, of the winter months, January (which had the greatest increase in urban-rural differences in mean temperatures) showed a heat island effect beginning in the late 1960s (Figure 3-2a). The winter months of January to March showed a significant increase in heat island i.e. differences between city and rural temperatures, over the years 1920 to 2000 (Figure 3-2b). The subsequent months April to June did not show significant increases (data not shown).

3.3.3 Urban versus rural phenology data

Mean first bloom dates for seven plant species with abundant observations in the study area are presented in Table 3-2. We minimized environmental variation in the analysis of these biological response data by restricting the rural observations to those from the northern two-thirds of the Central Parkland natural region (ASRD 2005). Five of these species flowered earlier in the city than the same species in rural areas by 1.7 to 5.4 days. Significant urban-rural differences were noted for these plants: the woody species *Populus tremuloides* (which shows the largest difference at 4.5 days earlier bloom in the city), *Amelanchier alnifolia, Prunus virginiana* and *Elaeagnus commutata*; as well as the herbaceous (non-woody) *Galium boreale*. The herbaceous *Anemone patens* showed no significant differences in bloom times, but the distribution of this native plant is largely restricted to uncultivated sandy habitats outside the city. City data reported for this species may include bloom dates for the very similar garden cultivar *Anemone rubra,* which blooms later than the wild *A. patens*. There may be a small effect of species' pollination strategy in our results: *P. tremuloides* is wind pollinated but the other species are insect pollinated. In central Europe, the "start of spring" phenophases i.e. first bloom of the herbaceous *Galanthus nivalis* and the woody *Forsythia* plants were about 4 days earlier in the city, but later or 'full spring' events were less than 2 days earlier (Rötzer et al. 2000). In our analysis however, species position in the bloom sequence showed no clear relation to the urban-rural differences, a result also found by Jochner et al. (2012).

Time series of first bloom for the five species with significant urban-rural differences are shown in Figure 3-3. Standard errors for individual years of urban and rural least squares means are indicated by transparent ribbons, and reflect the abundance of observations as well as variation in the reported bloom dates.. *Amelanchier alnifolia* (saskatoon or serviceberry) is a berry-producing shrub that is well known, widely distributed, and blooms for a relatively short period: an ideal phenological indicator plant. On a provincial basis it had the largest number of observations: 4890 records over 1987-2006 (Beaubien and Hamann 2011b). In comparison, *Populus tremuloides* (aspen poplar) had 2840 observations over the 20 years. *Elaeagnus commutata* (wolf willow, silverberry), which blooms later than *A. alnifolia*, had 2100 observations.

The mapped interpolation (Figure 3-4) clearly showed the heat island effect on spring plant responses for two species. Bloom data for the larger study area (Figure 3-1) showed that *P. tremuloides* had a wider variation in bloom time than the later blooming *A. alnifolia*. Start of season species, i.e. those that are the first to bloom in the spring, tend to show more variability in blooming dates than later-appearing species (Bertin 2008).

3.3.4 Historic versus recent phenology data

Bloom times for the recent 1987 to 2006 PlantWatch data were generally earlier in urban than in rural areas (Table 3-2). Further, both urban and rural bloom times for the 1987 to 2006 period were much earlier than historic bloom data from 1936 to 1961 (Table 3-3). Recent urban bloom times were on average 5.8 days earlier than the historical data, and recent rural observations were 3.7 days earlier than historical data. Thus, we can infer that approximately one third of the plant response observed in urban areas was caused by an increasing urban heat island effect over time (2.1 days advance more than rural). The remaining two thirds of the plant response (3.7 days advance, also observed in rural settings) can be attributed to climate warming in the general area.

P. tremuloides blooms or sheds pollen on average in mid April, in the rural area outside Edmonton. As urban-rural temperature differences were greatest in the coldest winter months, it makes sense that the biggest urban-rural plant development difference (about 5 days) was for this first species in our bloom sequence. Rural central Alberta has seen the greatest climate warming in early winter and much less warming in spring (Beaubien and Hamann 2011a). Adding these 5 days to the area climate change signal: a 14-day shift to earlier bloom in rural Central Parkland over the 70 years 1936 – 2006 (Beaubien and Hamann 2011a), we get a shift of 19 days in the city up to 2006. This trend of 0.20 days/ year is smaller than the 0.27 days/year reported in Beaubien and Freeland (2000): a 26-day shift to earlier bloom over the longer period 1901 to 1996. However this earlier study used combined data from the city and surroundings (100 sq km). Factors influencing the varying results include the differing data selection areas, time periods and also weather factors: from 1996 to 2006 there were several cold and late springs in central Alberta.

While *P. tremuloides* shifted by two weeks to earlier bloom over 70 years in rural Central Parkland, *A. alnifolia* had little overall change (Beaubien and Hamann 2011a). But both species showed significant urban-rural differences over the 20 years 1987 -2006 (Table 3-2). Note that different plant species and phenophases (growth stages) react differently to various environmental influences including temperature (Bertin 2008, Wolkovich et al. 2012). In general (urban effects aside), plant species that bloom at the start of spring show greater trends to earlier blooming over the years than plants that bloom later in the spring (Bertin 2008). These 'start of spring' growth stages respond more strongly to temperature than the late-spring phenophases (Menzel et al. 2006, Neil and Wu 2006, Wolkovich et al. 2012) and early spring temperatures also show greater urban-rural differences (Rötzer et al. 2000).

3.3.5 Implications for Society and the Environment

The urban heat island has potential implications for ecological interactions, human health, and economic adaptations to warming. Cities may help in future ecological adaptation to climate warming by acting as warm oases for plant species whose distributions are shifting northwards. These urban heat islands could act as testing grounds for agricultural crops or southern tree species. Cities may also be first harbours for invasive plants that require warmer conditions. Common ragweed (*Ambrosia* sp.*)* was shown to grow faster and release allergenic pollen earlier in cities (Ziska et al. 2003) and city dwellers may suffer allergies for longer periods through earlier exposure to city pollen (Jochner et al. 2011). Shifts to earlier plant development may threaten the balance of trophic interactions in the city environment (Neil and Wu 2006). For example, earlier spring plant development in cities can affect pollinators such as bees as well as nesting birds' foraging success (Dixon 2003, Luo et al. 2007) and can reduce the seed-set of bee-pollinated plants (Kudo et al. 2004). Climate warming in central Alberta may increase the risk of damaging frost for the first species to bloom in the spring (Beaubien and Hamann 2011a), but this may be partially mitigated by the longer frost-free season in urban areas.

Ground-based phenology observations, such as those used in this study from the Alberta PlantWatch program, offer important advantages in understanding the biotic response to climate warming. Remote sensing of vegetation suffers from insufficient temporal precision to provide accurate measures of 'start of spring' (White et al. 2009) and artificial warming experiments have been shown to underpredict greatly trends to earlier flowering and leafing (Wolkovich et al. 2012). But programs that engage the public in reporting plant phenology (e.g. Canada PlantWatch) can obtain accurate and abundant data from a variety of plant species from both urban and rural areas (Beaubien and Hamann 2011b). While urban areas can act as microcosms to assist in adapting to the future effects of warming, rural data on plant response are needed for an unbiased measure of climate change, and to clarify the considerable contribution of the urban heat island.

3.4 Conclusions

Plant phenology provides useful data to understand the effects of climate change, but clarification is needed to separate the influence of the urban heat island from that of general climate warming (as shown by rural phenology data). Edmonton's population increased rapidly from 85,470 in 1936, the start of the study period, to 730,372 residents in 2006, with a corresponding increase in the heat island effect. Winter temperatures for January to March showed significant differences between Edmonton city and the rural Calmar station, with January temperatures showing the most urban- rural differences. Using abundant data for both rural and urban locations we found differences in bloom time ranging from 1.7 to 4.5 days for the two recent decades (1987 to 2006), with the earliest plant species in our sequence, *Populus tremuloides* (aspen poplar) showing the biggest urban - rural difference. A comparison of the recent period with a historic phenology dataset (1936-1961) reflecting a period before the heat island really developed, showed that the city accounted for a third of the total warming to which plants were exposed. A general warming signal over the last 70 years accounted for two-thirds of the observed phenology trends in urban areas.

Table 3-1 Growth of Edmonton city. Edmonton census data for the beginning and end of an earlier phenology program (1936-1961), and for data analyzed from the Alberta PlantWatch program (1987-2006). The earliest and latest census data are given for reference as well (City of Edmonton 2012, Statistics Canada 2012). (n/a means data not available for the city plus urban fringes area)

Year	Edmonton city population	Greater Edmonton area population	
1901	2,626	n/a	
1936	85,470	n/a	Pre-heat island observations (1936-1961)
1961	276,018	n/a	
1987	576,249	802,353	Presumed heat island effects (1987-2006)
2006	730,372	1,034,945	
2011	812,201	1,196, 300	

Table 3-2 Means of day of first bloom (Mean) for the period 1987-2006 were calculated as least squares means, accounting for unequal number of observations among years. The number of observations over all years (N), and the standard error (SE) of the means and differences are given as well**.**

		Rural			Urban			Urban - Rural		
Species' Latin and common names		N	Mean	SE_{Mean}	N	Mean	SE_{Mean}	Diff	SE_{Diff}	
Anemone patens	Prairie crocus	129	107	0.7	14	108	2.2	0.9	2.3	
Populus tremuloides	Aspen poplar	169	106	0.5	44	102	1.0	-4.5	1.1	***
Amelanchier alnifolia	Saskatoon	218	137	0.3	70	133	0.5	-3.5	0.6	***
Prunus virginiana	Chokecherry	195	145	0.5	60	144	0.8	-1.7	1.0	**
Elaeagnus commutata	Wolf willow	82	153	0.9	34	150	1.4	-3.6	1.7	*
Galium boreale	Northern bedstraw	147	169	0.7	35	165	1.4	-3.4	1.5	**
Achillea millefolium	Yarrow	154	178	1.0	22	179	2.2	1.2	2.4	

*) $p<0.05$, **) $p<0.005$, ***) $p<0.0001$

Table 3-3 Comparison of historic and recent bloom times. Means of day of first bloom for the period 1936-1961. The number of years with observations (1936-1961) and the difference in days from this earlier period to the urban and rural means for the 1987-2006 period (Table 3-2) are also given. Standard errors could not be calculated because data for the 1934-1961 period were reported as annual means.

Species	Years of observations between 1936-1961	1936-1961 mean (day of year)	1987-2006 urban difference (days)	1987-2006 rural difference (days)
Anemone patens	16	115	-7.5	-8.5
Populus tremuloides	26	116	-14.2	-9.7
Amelanchier alnifolia	36	137	-3.7	-0.2
Prunus virginiana	23	149	-5.2	-3.5
Elaeagnus commutata	24	156	-6.4	-2.8
Galium boreale	24	170	-4.4	-0.9
Achillea millefolium	18	178	0.9	-0.3

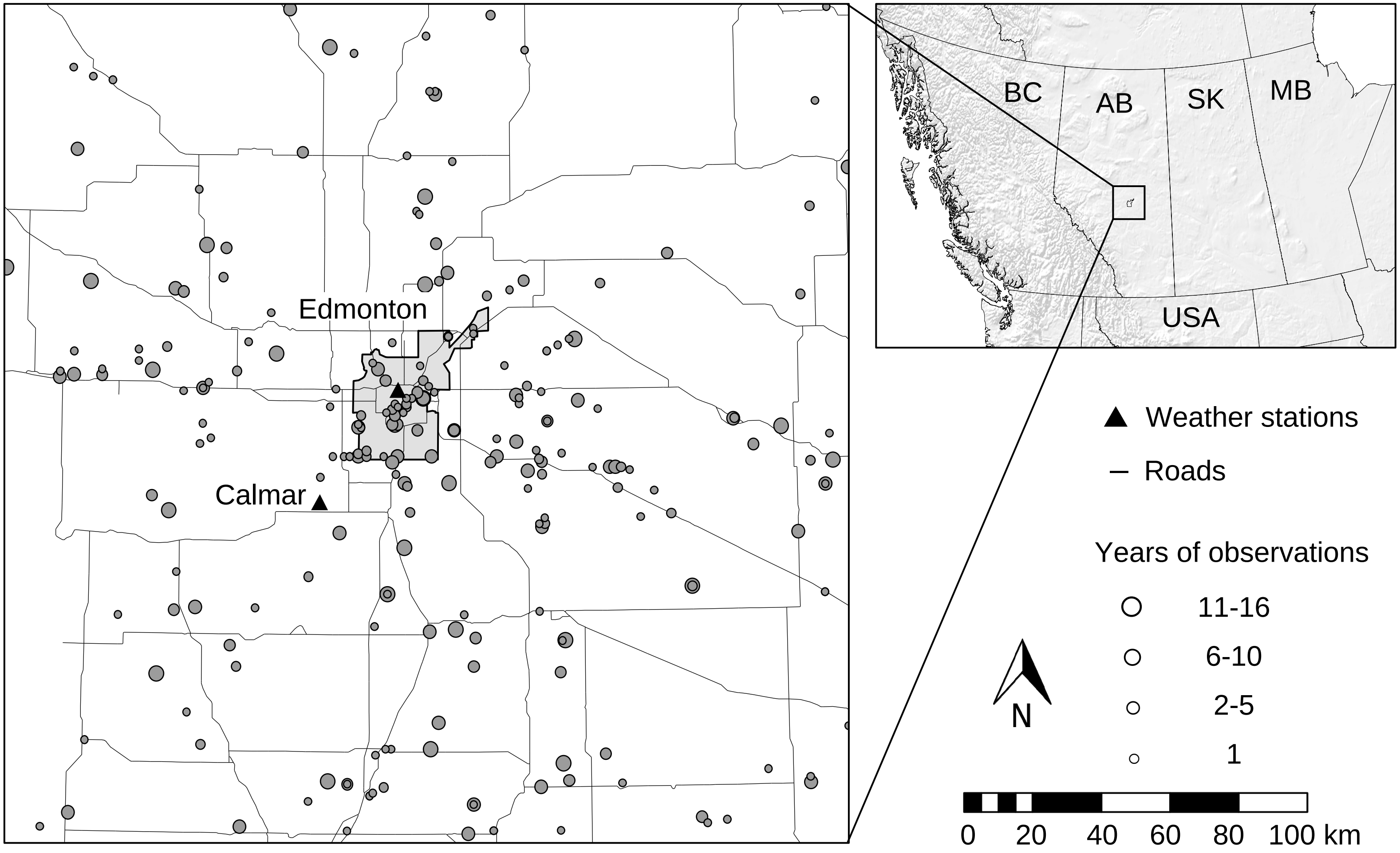

Figure 3-1 Study area, 225×225 km in size, centered around Edmonton, Alberta.

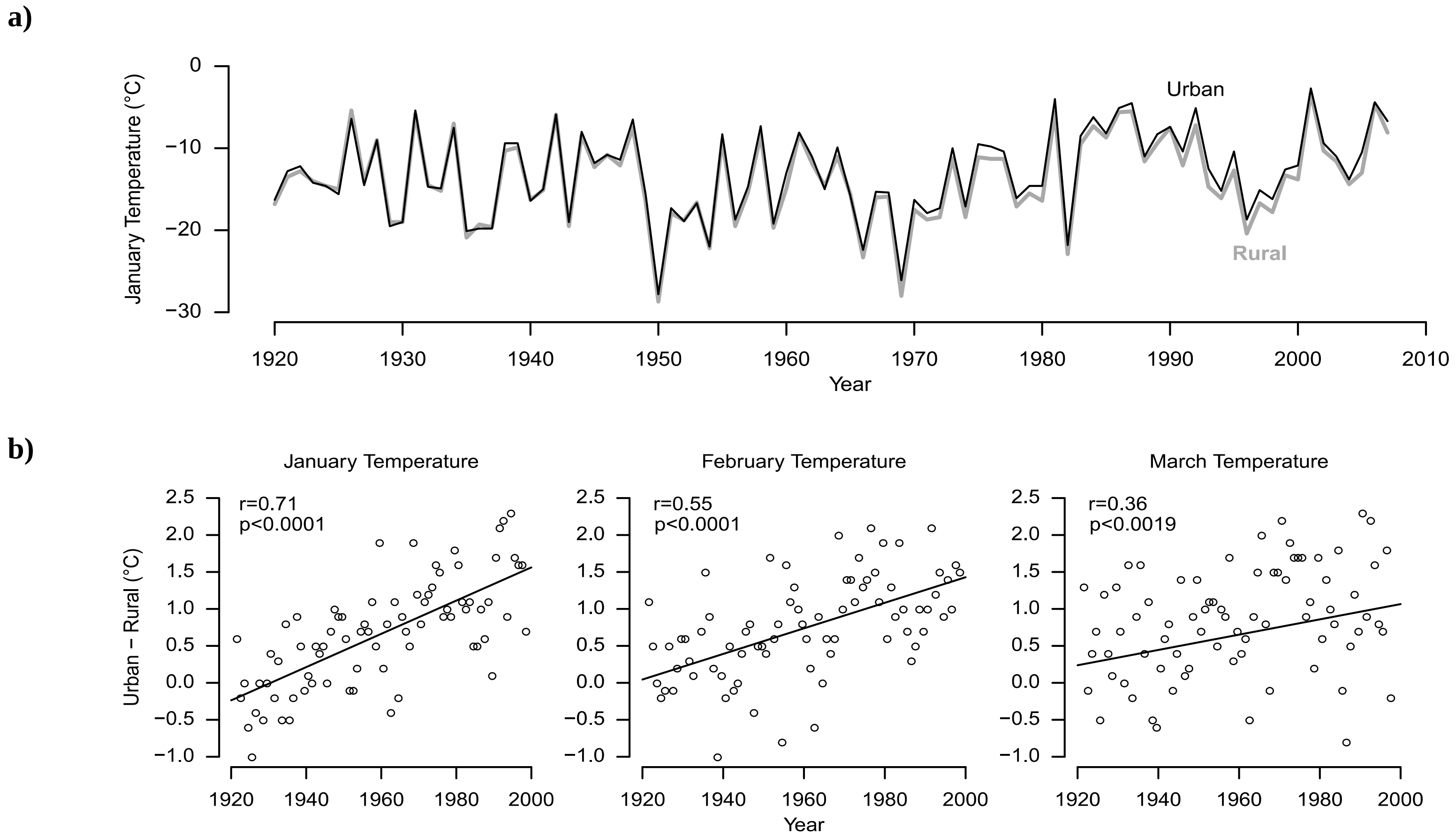

Figure 3-2 Temperature records for the urban weather station Edmonton City Center Airport versus the rural station of Calmar, approximately 20km outside of Edmonton's built-up area. A heat island effect becomes visually apparent in the late 1960s for mean January temperature (a), and the difference between rural and urban temperature records significantly increase over time for January to March mean temperatures (b). There is no significant heat island effect for temperatures in April and later (data not shown).

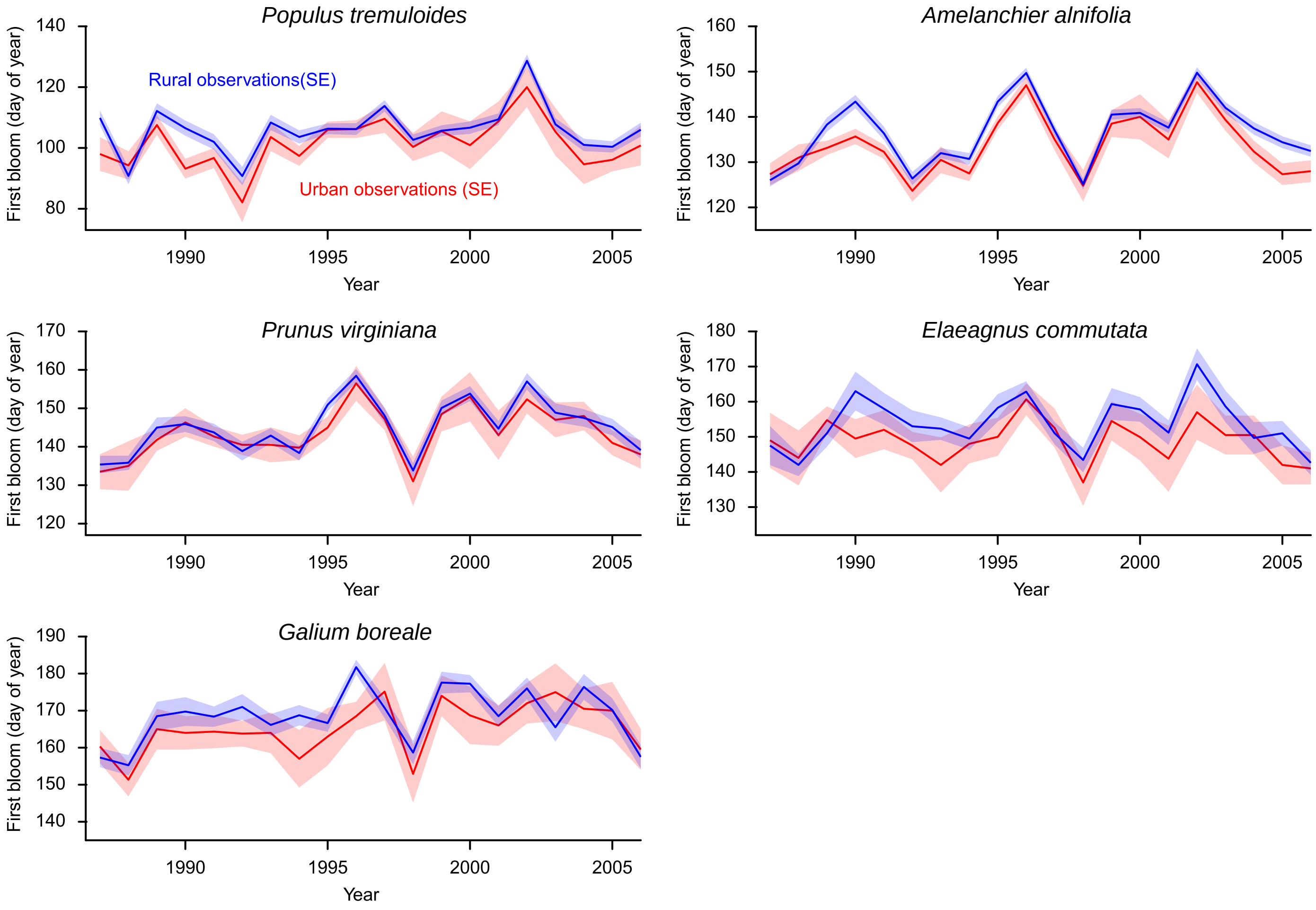

Figure 3-3 Time series of first bloom for species that showed a significant difference between urban (red) and rural (blue) observations (Table 3-2). Standard errors of urban and rural least squares means are indicated by semi-transparent ribbons.

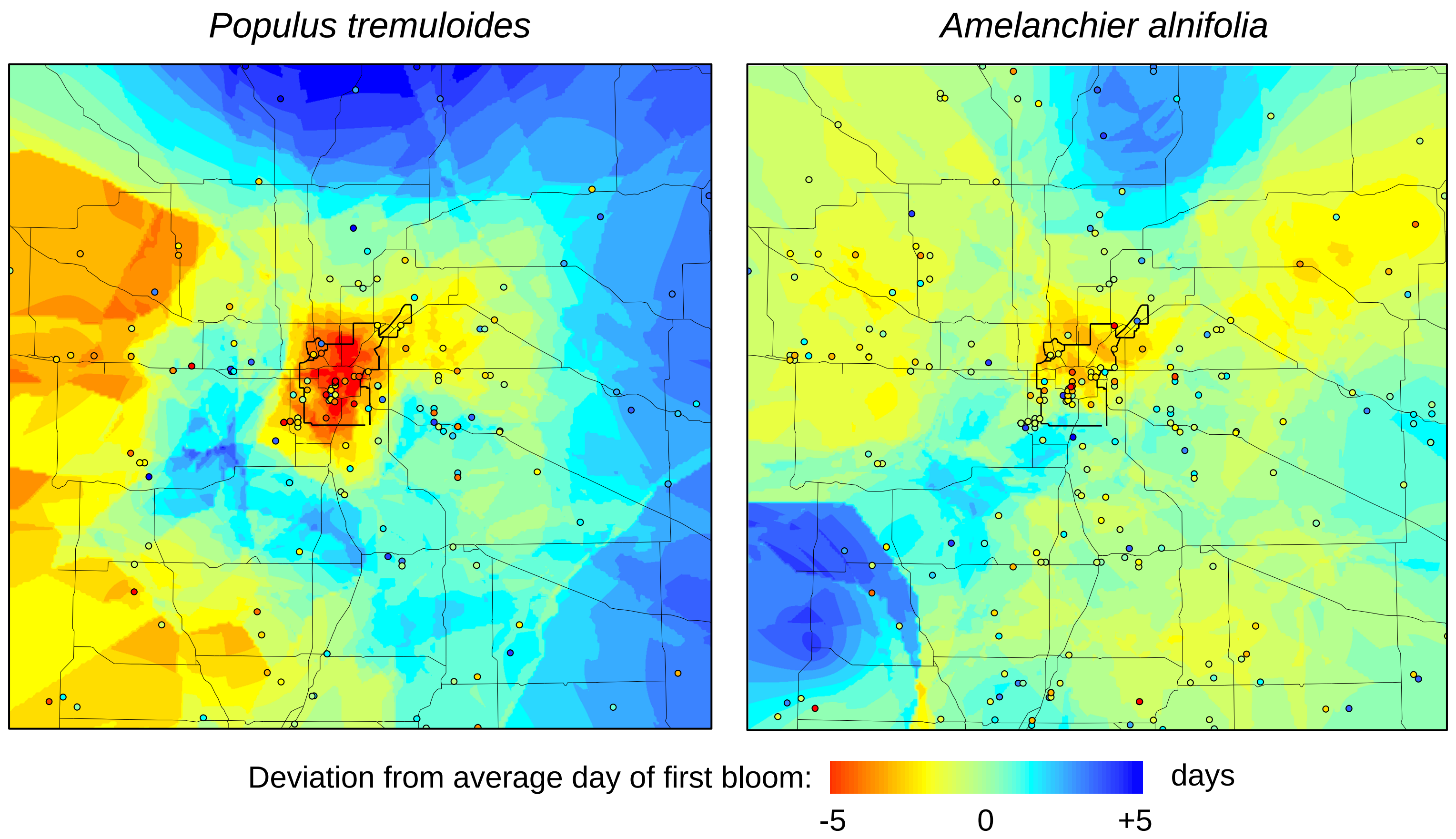

Figure 3-4 Interpolated deviation from the average day of first bloom for a 225×225 km area centered around Edmonton, Alberta. Heat islands indicated by earlier bloom times are visible for the two species with the best spatial data coverage and the most accurate reporting of bloom times, aspen poplar (*Populus tremuloides* Michx.) and saskatoon (*Amelanchier alnifolia* Nutt.). Colours of dots (data points) and background represent deviations from mean first bloom date**.**

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Chapter 4 - Plant Phenology Networks of Citizen Scientists: Recommendations from Two Decades of Experience in Canada[2]

Summary

Plant phenology networks of citizen scientists have a long history and have recently contributed to our understanding of climate change effects on ecosystems. This paper describes the development of the Alberta and Canada PlantWatch programs, which coordinate networks of citizen scientists who track spring development timing for common plants. Tracking spring phenology is highly suited to volunteers and with effective volunteer management, observers will stay loyal to a phenology program for many years. Over two decades beginning in 1987, Alberta PlantWatch volunteers reported 47,000 records, the majority contributed by observers who participated more than nine years. We present a quantitative analysis of factors that determine the quality of these phenological data and explore sources of variation. Our goal is to help those who wish to initiate new observer networks with an analysis of the effectiveness of program protocols including selected plant species and bloom stages.

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4.1 Introduction

Many parts of the world are experiencing rapid climate change, and biological data are needed to understand how ecosystems are responding. We have previously shown trends to earlier spring bloom times over the last century in response to increased winter and spring temperatures (Beaubien and Freeland 2000, Beaubien and Hamann 2011). This article tells the story of harnessing the energy of citizen scientists to track the effects of climate change across Canada. Specifically, we describe the development of the Alberta and Canada PlantWatch programs, and we provide a quantitative analysis of factors that determine data quality. This analysis is based on the Alberta PlantWatch program, the longest-running plant phenology network in Canada for recent decades, drawing on 47,000 records reported between 1987 and 2006. Data quality is an important consideration for volunteer citizen science programs (Bonney et al. 2009; Delaney et al. 2008) and our analysis of program protocols is presented to help those planning new networks. Because the article is written for scientists who wish to recruit citizens for a plant phenology network, we offer some additional information on program development in the form of an extended introduction below.

4.1.1 History of Canadian phenology networks

The first large-scale Canadian phenology observer network started in Alberta in 1973. This decade-long survey of bloom dates of wild plants was initiated through the Federation of Alberta Naturalists (Bird, 1982) and was revived as the Alberta

Wildflower Survey in 1987 (Beaubien and Johnson 1994). This program has continued since that time, renamed Alberta PlantWatch in 2002. This project began as part of an MSc thesis (Beaubien 1991) supervised by ecologist Dr. Walter Moser, with the goal of exploring the potential for phenology in Alberta. By 1995, E. Beaubien had added to the Alberta program a Web-based program called Prairie PlantWatch. In 1997 it was renamed Canada PlantWatch with more indicator plant species added to gather data from Canada's west coast, eastern provinces, and Arctic (Schwartz and Beaubien 2003, Beaubien and Hall-Beyer 2003). In 2000, the federal Environmental Monitoring and Assessment Network led by Tom Brydges of Environment Canada, added PlantWatch to their other NatureWatch citizen science activities (*www.naturewatch.ca*). Coordinators were found for all thirteen provinces and territories.

Since 2002, the Canada PlantWatch program has been the umbrella organization for several regional programs in Canada's provinces and territories. The position of national coordinator has been a full-time position paid for by Environment Canada, in charge of four citizen science programs including PlantWatch. The coordinator had a budget to develop promotional materials and maintain the website (*www.plantwatch.ca*). In recent years a small portion of the budget was provided to regional coordinators to cover the annual costs of promotion and mailing to observers. Promotional materials and program protocols were developed in conjunction with regional coordinators, who met annually during the initial development of the program to coordinate their efforts and exchange ideas. Regional coordinators are not paid specifically for their contributions to the PlantWatch program, but they typically hold positions at universities, botanic gardens, or non-profit nature organizations where PlantWatch-related work fits under the institutions' general mandate.

The main goal for this Canadian program is to understand better both temporal and geographic patterns of how vegetation is responding to climate warming. Some of the results from this program are now appearing in the scientific literature (Beaubien and Hamann 2011, Kross et al. 2011, Vasseur et al. 2001).

4.1.2 Program promotion and volunteer recruitment

In 1988, an illustrated booklet describing the Alberta Wildflower Survey and 15 selected native plants was distributed to potential observers. Over the period 1987-1990, promotion included articles in all major Alberta newspapers and 14 society or government newsletters, as well as 13 talks, 2 radio interviews and 4 posters at conferences (appendix 5 in Beaubien 1991). A diverse group of volunteer observers was engaged, including people who recorded weather variables for Environment Canada, and fire tower staff from northern forests (Koch 2010). Other promotional efforts included the publication of a pocket-size booklet 'PlantWatch: Canada in Bloom' in 2002, with an updated edition released in 2010, which supports identification and provides reporting instructions for 39 species.

Another important means of communication are Websites and on-line tools. Alberta observers who wish to learn about PlantWatch, or report their data electronically, can choose from two sites: our Alberta Website (*plantwatch.fanweb.ca*) or the Environment Canada Website (*www.plantwatch.ca*). Observers can determine location information of their observations with on-line tools, report bloom or leafing data including photos, and edit their past data. New Alberta observers receive a mailed package with booklet, extra ‘how to’ information, and a paper data sheet. The majority of Alberta observers report data on paper or emailed data sheets rather than online. Reported phenology observations are also downloadable for research on the Environment Canada Website.

4.1.3 Volunteer motivation and retention

We have made an effort to retain PlantWatch observers for many years to build their knowledge of plant identification and spring development stages, thus increasing the likelihood of accurate reporting. For example, a new observer may need several weeks in late winter and spring to learn to distinguish male from female trees in a complex species such as the aspen poplar tree *Populus tremuloides*. To be able to reward effectively and retain volunteers, coordinators need to know why observers join PlantWatch. A study of motives for long-term participation by 150 volunteers in an ‘Adopt-a-Stream’ program revealed the following as most important: enjoying learning, helping the environment, feeling needed, having time for reflection, and benefitting from a well-organized program with good leadership (Ryan et al. 2001). No specific studies of PlantWatch volunteers’ motivations have yet been published.

In Alberta, PlantWatch participants receive regular communication by mail and email with thanks or reminders to send data. Newsletters summarize interesting comments from observers about the relative earliness of the season, abundance of flowers or berries, effects of spring snow or frost, and insect activities. In some years, results of data analysis were provided. Personal notes were added if needed, to request details on locations or dates submitted and to answer observers' questions. Believing that it is better to keep a known observer for as long as possible rather than to find and train new people, EB sent observers reminder newsletters for up to four years after they stopped submitting data. Departing volunteers were sent a thank you letter and a certificate.

It is important to make the PlantWatch volunteer experience as enjoyable and flexible as possible to maintain interest in the program. Observers can collect data near their homes at times that suit them, and report on just one plant if their time is limited. Participants gain awareness of the natural world around them; this field-based knowledge builds science skills and benefits society as it creates the commitment needed for true stewardship and conservation of wild habitats. PlantWatch encourages youth to make observations outdoors on a regular basis in spring. There is now a 'nature deficit disorder' among children, whose increasing use of electronic devices coincides with reduced contact with nature (Louv 2008). To encourage teachers, a PlantWatch Teacher Guide was posted on the Alberta Website in 2001and then updated in 2009 in English and French (*www.plantwatch.ca*). A wallchart helps maintain program visibility in schools and parks during the busy spring season (*plantwatch.fanweb.ca*).

Relying on volunteers with a long-term commitment to the program allows for the gathering of quality data from a wide area at a manageable cost. The advantages of using volunteers over paid technicians are that they are committed, often more careful, mature, and will participate for many years (Droege 2007).

4.1.4 Goals for this paper

The following analysis focuses on the findings of Alberta PlantWatch for the years 1987 to 2006. We use these data to provide a quantitative analysis of factors that determine data quality to aid the development of program protocols and species selection. We ask: How do the observed plant species differ in both timing and variability of bloom date, and how suitable is each for volunteer observation? How do the observed bloom phases differ in variability? How long did observers stay involved with Alberta PlantWatch, and how did this affect the quantity and quality of data reported?

4.2 Materials and methods

4.2.1 Species selection

The main criteria for including a plant species for observation by volunteers are wide distribution, abundance in suitable habitat, and ease of recognition. Plant species must be perennial (not annual), so that the timing of bloom does not depend on the seeding or germination time. The species should preferably be monoecious (having both male and female flower parts on the same plant). In dioecious species such as poplar trees, male plants should be observed rather than female plants for which exact bloom times are often hard to observe. Species complexes with many species or subspecies of similar appearance that may have different flowering times should be avoided. Because the primary objective is to track climate variability and climate change, plants that bloom at the start of spring are preferred. Their bloom timing is usually more closely linked to temperature accumulation than plants that bloom later in the season (Fitter and Fitter 2002).

Flowers of selected species should bloom for a short period to minimize observer error in observing bloom stages. Flowers should ideally stay open once bloom begins so that first bloom can be clearly identified. For example, lilacs meet this criterion but dandelions close on cloudy days. The degree of herbivory is important; selected plants should have flower buds that are not attractive to caterpillars, rabbits, deer, etc. It can be both useful and problematic to select native plants that have horticultural cultivars that look similar and are hard to distinguish from a wild specimen, because the genetics and phenology of cultivars may vary from those of wild populations. Cultivars of the plant could be distributed to observers as cloned plants that are identical genetically, thus removing this source of variation in bloom date. However, if cultivars exist for a plant species, it is necessary to ask observers to report whether a garden plant or a wild plant was observed. For an extensive discussion of how to select organisms for phenology studies see Leopold and Jones (1947).

There are obviously few species that fit all these criteria well. The larger the geographic area of the observer network, the more difficult it is to find species that are, for example, abundant everywhere and without similar-looking related taxa. Some subjective judgment needs to be applied. Alberta PlantWatch species fulfill most of the selection criteria (Table 4-1).

4.2.2 Observer protocols

Observers were instructed to report the calendar date for bloom phases. First bloom was defined as “the first flowers open in three different places on a woody shrub or tree”, or “first flowers open in a patch of herbaceous plants”. Mid bloom was defined as “50% of flower buds open” and full bloom was defined as “90% of flower buds open”. Observation of full bloom ended in 2002, when protocols were adjusted to match better those used in Europe. The purpose of reporting at least two bloom stages was to increase the accuracy of the data, as observers would need to revisit the plants over a period of time.

Secondly, observers were asked to report the location of their plants. Most rural observers used an Alberta coordinate system of township, range, section, and quarter section, a system that represents geographic locations to the nearest 400m. Since the Web-based program began in 1995, observers have been asked to georeference their data with exact geographic coordinates using Web-based maps or a global positioning system (GPS). On the PlantWatch Websites, observers now zoom in to their observed plant’s location on a map and that latitude/longitude is automatically added to their data report.

Thirdly, observers were also encouraged to tag individual shrubs or trees, or patches of small plants, and to re-visit those plants every year. The recommended frequency of spring visits was at least every two days to ensure that first bloom was accurately observed. Ideally, observed plants should be located on a flat area and away from heat sources such as buildings. To deal with habitat variation, we asked observers to add environmental details to indicate whether the plant was in a sunny or shady location, on a flat area or on a slope, and in what proximity to buildings.

4.2.3 Analysis

For statistical analyses we calculated least squares means (lsmeans) for day of year for phenology observations by species, bloom phase, year, and ecosystem using the general linear model procedure PROC GLM of the SAS statistical software package (SAS Institute 2008). Ecosystems were based on the Alberta Natural Region and Subregion system (Natural Regions Committee 2006) and we used this system to account generally for phenological differences between regions of Alberta. We further calculated variance components to attribute the total variance in the phenological dataset to various possible causes. Variance components were estimated with the restricted maximum likelihood method implemented with PROC VARCOMP (SAS Institute 2008). For this analysis we worked with a reduced dataset including only the 15 species that were part of the program since the beginning in 1987. Because environmental data on plant shading and exposure were transcribed only for the years 1996-2002, 2005 and 2006, these nine years were used. The main effects and treatment levels that we included for the variance partitioning were years (nine years of data), species (15 species), phase (first bloom, mid bloom and full bloom), location (20 natural subregions), shading (sunny, half shade, full shade), and exposure (nine treatment levels). The nine treatment levels were a combination of slope and aspect. We distinguished two slope levels that were reported as flat, versus gentle or steep slope. Aspect was summarized for analysis as south facing (S, SE, SW), north facing (N, NE, NW), west or east facing. Summary statistics and variance components were visualized with histograms, box plots, and area charts using the R programming environment (R Development Core Team 2008).

4.3 Results and discussion

4.3.1 Location and number of observations

The reported observations of the Alberta PlantWatch program between 1987 and 2006 are shown in Figure 4-1, broken down by natural subregion. Most of the observations were reported from the Central Parklands region of Alberta and the Dry Mixedwood region 2, immediately north of the Central Parklands. The area of next most abundant observations is the city of Calgary. This reflects the human population distribution of Alberta and much of the agriculturally-productive zones of the province. It may also reflect the area of most promotional effort at the beginning of the program. The chart of numbers of observers over the years (not shown) has a very similar shape to Figure 4-1.

At the start in 1987 and 1988, the Alberta PlantWatch program built on the success and popularity of the Federation of Alberta Naturalists program that had run in the previous decade. About 200 naturalists including previous observers were contacted and 3000 copies of a 22-page illustrated booklet describing the Alberta Wildflower Survey were distributed to potential observers at the beginning of the program. The early promotion resulted in a rapid recruitment and a peak of more than 2,500 observations in the second year (Figure 4-1). Interestingly, there was a steady decline after the initial promotional effort, and again after a second peak. This pattern reflects the time commitment of the program coordinator (E. Beaubien), who was engaged with graduate research until 1991. After completion of her thesis she was again able to devote a major portion of her time to engaging and communicating with observers. This increased observations to a peak of 3,500 observations in 1993. These intensive promotional efforts decreased after the program was firmly established and energy was diverted to establishing a national Web-based PlantWatch.

The number of observations in Alberta did not increase either after Canada PlantWatch was established, or after on-line reporting became available in 1995. The numbers actually decreased steadily from the 1993 peak (Figure 4-1). It is therefore quite apparent that the success of a volunteer network relies considerably on the efforts of local coordinators to communicate with potential and existing observers. Though considerable promotional energy was devoted to engaging school classes over the two decades in Alberta, little data resulted. Teachers were initially enthusiastic, with students tagging plants and many observing dates in spring, but the step of actually reporting data was often missed. This could be remedied in future by regular spring reminder emails or incentive programs.

Even though the efforts of regional leaders are key to the success of a volunteer network, it is useful to have a national umbrella organization. For Canada, PlantWatch was organized regionally by province and territory, but it could potentially involve finer divisions, where local champions of the program can better maintain personal contact with the volunteers. In our experience, the regional coordinators were very effective in giving promotional talks and handling questions from the public. On the other hand, national coordination provided essential cohesiveness to the program and helped to minimize costs of promotional materials and Website development and maintenance. The national coordinator found new regional coordinators, gathered their program suggestions, hosted conference calls, and supervised updates of Website and promotional materials. Meetings at coordinator workshops helped regional coordinators share ideas for projects such as teacher guides, posters, and brochures and initiate applications for funding. This work resulted in numerous grants for at least the northern coordinators to promote involvement of citizens in tracking data needed to reveal the effect of climate change.

4.3.2 Variability of observations by species and phase

To quantify the variability in phenology records that was due to the observer error (or other non-documented effects) as opposed to being caused by climate, we used a variance partitioning approach. Figure 4-2 shows the residual variation of phenology observations, after effects of year, location (but not species and bloom phase) have been accounted for as least squares means in the general linear model. Figure 4-2 includes plant species observed since the beginning of the program and which have the largest amount of data. In addition, we report number of observations, the median bloom date, and the inter-quartile range (25% of observations above and below the median) of bloom date for all species (Table 4-2). We followed the scientific nomenclature of Moss (1983). We found that the least variable species (smallest values of inter-quartile range) were *Amelanchier alnifolia* (saskatoon or serviceberry), *Elaeagnus commutata (*wolf willow*)*, *Lilium philadelphicum* (western wood lily) and *Prunus virginiana (*chokecherry). These are species that bloom quickly, and are thus better phenology 'indicator' plants (Leopold and Jones, 1947). Other useful species were *Anemone patens* (prairie crocus) and *Populus tremuloides* (aspen poplar), because they bloom early, are widespread and the bloom dates show reasonably low variation (Figure 4-2, Table 4-2).

Interestingly, the variability in bloom phases was only moderately increased for the full bloom phase with average inter-quartile ranges of 7.6 days, 7.4 days, and 8.9 days for first, mid, and full bloom across all species, respectively. A paired t - test revealed that there was no statistical difference between first and mid-bloom, but the full-bloom inter-quartile range differed significantly from the earlier phases with p-values < 0.001. We conclude, somewhat to our own surprise since first bloom is generally easier to recognize, that first and mid bloom observations are equally accurate in this provincial data compilation. In future they could possibly be combined using a species specific adjustment. If the total number of observations is low, and standard errors of the estimates could be improved by increasing N, a more accurate first-bloom estimate for *Achillea millefolium* (as an example) may be obtained by including mid-bloom values minus the difference calculated from median values in table 4-2 (183–174=9 days). If the data are normally distributed all calculations could be done using means.

4.3.3 Variance partitioning

Next, we ask if the residual variation shown as boxplots in Figure 4-2 can be attributed to causes other than species, phase, year, and location. Results from partitioning of variance components are shown in Table 4-3. Additional factors included were environmental details for observed plants including exposure to sun or shade, position on flat land or slope with a directional aspect, and proximity to buildings. However, none of these additional factors contributed very much to the overall variation in the entire dataset. This does not necessarily mean that some of these factors were not important for at least some species in some locations. The effects of micro-climate due to slope and aspect clearly would have an effect on bloom times in steep ravines (Jackson 1966) or in mountainous regions. However, none of these effects could be generalized to be important for studies at a provincial scale.

After all reported species, phase, year, location, and environmental factors have been accounted for, we still have an 8.4% residual variance (Table 4-3). Potential explanations for this residual variation include unknown microsite effects, natural genetic variation in plant populations, or erroneous reporting of flowering dates. While this is difficult to quantify, we made an attempt to reveal residual variance that is caused by observer error. The expectation would be that long-term program participants, who often rely on familiar tagged plants, should report less variable data than one-time observers who may not correctly identify a plant or bloom stage. We therefore grouped our data into log-2 classes of the number of years an observer has been a participant in the Alberta PlantWatch program (Fig 3a). While we have many observers who reported only for one or two years, more than half of our data originate from observers who have stayed with the program for a decade or more (Fig 3b). It is interesting to note that their observations are just slightly less variable than data submitted by short-term observers (Fig 3c).

We think that it is essential for observers to be properly trained in recognition of species and phases, and that many years of experience observing plants contributes to better data. Also, long-term observers usually report on multiple species over many years (Fig 3b, class 9-16 years), contributing disproportionally to the amount of data. However, the residual variance for different observer groups in Figure 4-3c suggests that even data from one-time reporters are largely unbiased (i.e. not over- or underestimating the mean bloom dates), and almost as temporally precise as data provided by long-term observers. This would suggest that observer networks could focus on obtaining large numbers of observations regardless of how long individual observers stay with the program, without compromising data quality.

Our findings support other research that suggests that networks of citizen scientists can gather high-quality data for scientific research. An evaluation of 395 European monitoring projects of flora and fauna concluded that volunteer-based projects provide relatively reliable data and unbiased results (Schmeller et al. 2008). Bonney et al. (2009) report that ‘citizen science projects have been remarkably successful in advancing scientific knowledge’. A study by Delaney et al. (2008) suggests that even data collected by primary school students can provide quality biological data. We should note that other researchers report a more pronounced ‘learning effect’ where new participants in volunteer-based monitoring programs are the source for most of the variation in observer ability, with improvements in data collection over time (Dickinson et al. 2010).

4.4 Conclusions and recommendations

With respect to selecting suitable species for plant-watch programs, we can recommend a number of species that fit one or more of the desirable attributes of blooming early, over a relatively short period, with low variability, and that are easily identifiable: *Amelanchier alnifolia* (saskatoon), *Elaeagnus commutata* (wolf willow), *Prunus virginiana* (chokecherry), *Anemone patens* (prairie crocus) and *Populus tremuloides* (aspen poplar). Some of these species have North American or even circumboreal distributions. For setting up observer networks in other regions, related species such as *Populus tremula* in Europe might be taken into consideration.

With respect to observation protocols, our data suggest that it is useful to distinguish between first, mid, and full bloom phases, which represent sequential stages in individuals (trees and shrubs) or patches of smaller plants. All three stages provide data that can be used with appropriate adjustments to estimate any particular bloom stage, particularly if data are scarce for particular years, species, or regions. Data describing the micro-environment of observed plants, such as shading, proximity to buildings, or slope and aspect did not have a significant effect on bloom dates in our study. We think that further research restricted to particular species and locations might yield different insights, but our conclusion is that at least provincial or national scale analyses are not compromised if volunteers do not report such data.

We think that it is essential for observers to be properly trained in recognition of species and phases, and that many years of experience observing plants contributes to better data. We also found that long-term observers contributed disproportionally to the total amount of data reported. Nevertheless, our analysis suggests that even data from one-time reporters are unbiased and precise and that efforts to include, for example, school children, are a worthwhile endeavor. This result is supported by other publications on citizen science networks, although a ‘learning effect’ where new participants in volunteer-based monitoring programs are the source for most of the variation has been found by others.

To encourage and keep volunteers in this citizen science program, we need coordination that identifies and meets the needs and interests of observers, and provides appropriate training, frequent feedback, and rewards. As this support of volunteers requires considerable financial and other resources, government support is essential and has been the backbone of many long-term phenology networks in the United States and Europe. As Bonney et al. (2009) notes: “An effective citizen science program requires staff dedicated to direct and manage project development; participant support; and data collection, analysis, and curation. Such a program can be costly; the Cornell Laboratory of Ornithology’s current citizen science budget exceeds $1 million each year … Considering the quantity of high-quality data that citizen science projects are able to collect once the infrastructure for a project is created, the citizen science model is cost-effective over the long term.”

Table 4-1 Species included in the Alberta PlantWatch program and characteristics that affect species' suitability for phenology citizen science networks. "Abund." is species abundance in its habitat.

Species	Type	Distribution	Abund.	Similar taxa	Herbivory
Achillea millefolium L.	herb	throughout AB	high	one introduced	no
Amelanchier alnifolia Nutt.	shrub	throughout AB	high	none	occas.
Anemone patens L.	herb	throughout AB	high	none	yes
Artostaphylos uva ursi (L.) Spreng.	shrub	throughout AB	high	one frequent	no
Cornus canadensis L.	herb	forested AB	high	none	no
Dryas integrifolia M. Vahl, *D. octopetala* L.	shrub	alpine	high	two included	no
Elaeagnus commutata Bernh. *ex* Rydb.	shrub	forested AB	medium	none	no
Epilobium angustifolium L.	herb	throughout AB	high	none	yes
Fragaria virginiana Duchesne, *F.vesca* L.	herb	throughout AB	high	two included	no
Gaillardia aristata Pursh	herb	southern AB	medium	none	no
Galium boreale L.	herb	throughout AB	high	none	no
Larix laricina (Du Roi) K. Koch	tree	forested AB	high	one introduced	no
Lathyrus ochroleucus Hook.	herb	throughout AB	high	none	yes
Ledum groenlandicum Oeder	shrub	forested AB	high	none	no
Lilium philadelphicum L.	herb	throughout AB	low	none	yes
Linnaea borealis L.	shrub	throughout AB	medium	none	no
Pinus contorta Loudon	tree	western AB	medium	one frequent	no
Populus tremuloides (Michx.)	tree	throughout AB	high	one frequent	no
Prunus virginiana L.	shrub	throughout AB	high	one frequent	no
Saxifraga oppositifolia L.	shrub	alpine	medium	none	no
*Smilacina stellata (*L). Desf.	herb	throughout AB	high	none	no
Syringa vulgaris L.	shrub	introduced	medium	many cultivars	no
Taraxacum officinale Weber	herb	introduced	high	none	no
Thermopsis rhombifolia (Nutt.) Richards.	herb	southern AB	medium	none	no
Viola adunca J.E. Smith	herb	throughout AB	high	one rare	no

Table 4-2 Observation and phenology statistics for species included in the Alberta PlantWatch program. For both median bloom date and interquartile range (which is a measure of variation in bloom dates) variation due to year and location has been removed through variance partitioning.

	Number	Years of	Median bloom date			Interquartile range		
Species	of obs.	observations	First	Mid	Full	First	Mid	Full
Achillea millefolium L.	3516	1987 - 2006	174	183	190	11.0	11.3	14.1
Amelanchier alnifolia Nutt.	4889	1987 - 2006	137	141	143	5.0	4.9	5.7
Anemone patens L.	3600	1987 - 2006	104	111	116	8.1	8.1	9.0
Artostaphylos uva ursi (L.) Spreng.	134	2002 - 2006	137	145				
Cornus canadensis L.	196	2002 - 2006	160	168				
Dryas integrifolia M. Vahl, and *D. octopetala* L.	34	2002 - 2006	160					
Elaeagnus commutata Bernh. *ex* Rydb.	2112	1987 - 2006	153	158	163	6.1	6.6	7.2
Epilobium angustifolium L.	2955	1987 - 2005	188	196	204	8.6	9.1	12.3
Fragaria virginiana Duchesne, *F.vesca* L.	504	2002 - 2006	141	149				
Gaillardia aristata Pursh	1941	1987 - 2005	177	184	191	8.9	8.7	11.2
Galium boreale L.	3426	1987 - 2006	169	176	181	8.4	8.4	10.2
Larix laricina (Du Roi) K. Koch	64	2002 - 2006	128	134				
Lathyrus ochroleucus Hook.	2451	1987 - 2004	156	162	168	8.4	9.5	10.0
Ledum groenlandicum Oeder	93	2002 - 2006	160	168				
Lilium philadelphicum L.	2182	1987 - 2004	175	180	185	5.9	6.4	8.0
Linnaea borealis L.	1287	1987 - 2006	170	176	181	6.5	5.4	7.4
Pinus contorta Loudon	47	2002 - 2006	151					
Populus tremuloides (Michx.)	2836	1987 - 2006	106	110	113	7.7	6.8	7.1
Prunus virginiana L.	3204	1987 - 2006	146	150	153	6.4	4.9	5.5
Saxifraga oppositifolia L.	8	2002 - 2005	184					
*Smilacina stellata (*L). Desf.	2992	1987 - 2006	148	153	157	7.2	7.3	7.9
Syringa vulgaris L.	541	1997 - 2006	150	155				
Taraxacum officinale Weber	617	2002 - 2006	128	140				
Thermopsis rhombifolia (Nutt.) Richards.	3166	1987 - 2006	130	136	140	8.0	6.4	8.1
Viola adunca J.E. Smith	3965	1987 - 2006	130	135	140	7.4	7.1	9.4

Table 4-3 Variance in bloom date explained by different species, locations, bloom phases, and environmental factors. Variance components were estimated with the restricted maximum likelihood method.

Effect (treatment levels)	Variance component
Species (15 species)	72.7 %
Phase (first, mid, full)	9.6 %
Year (1996-2002, 2005, 2006)	5.5 %
Location (20 subregions)	3.7 %
Shading (sunny, half shade, full shade)	0.1 %
Exposure (N, E, S, W and slope)	0.1 %
Near building (yes, no)	0.0 %
Residual variance	8.4 %

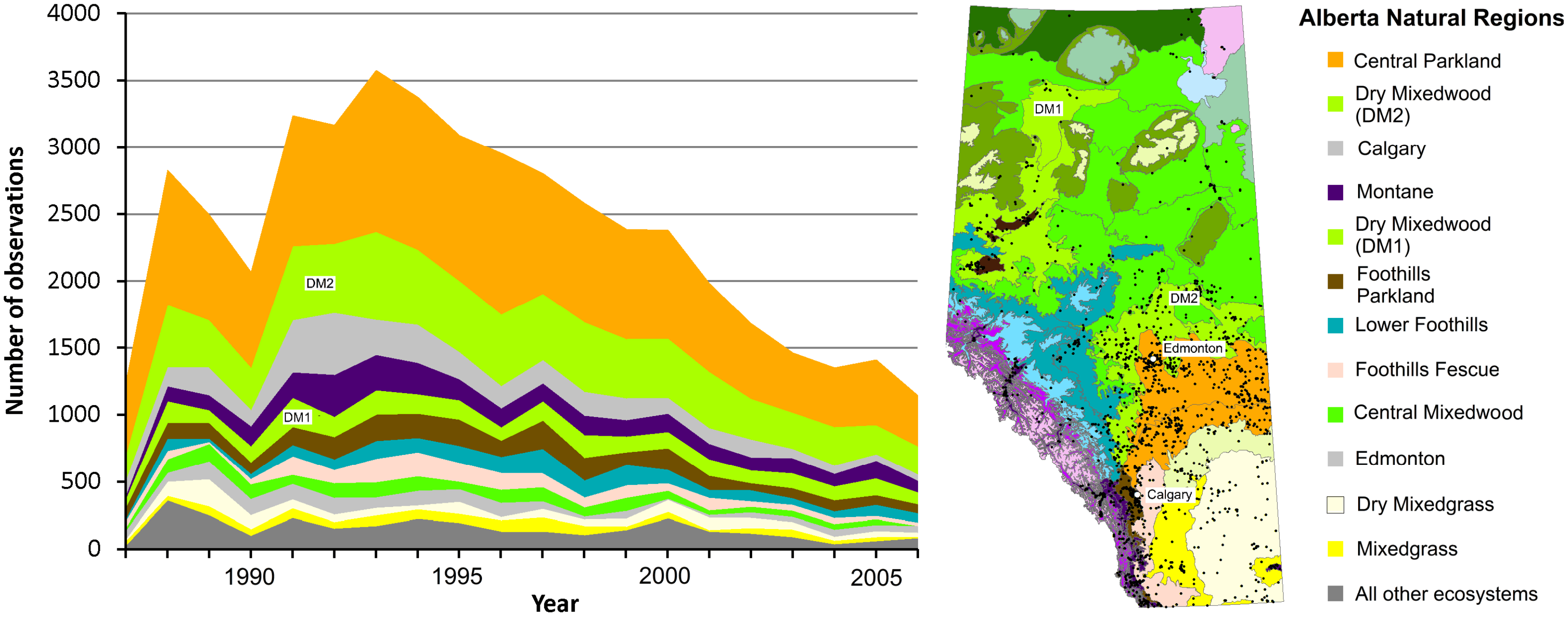

Figure 4-1 Locations and number of observations over the course of the Alberta PlantWatch program from 1987 to 2006. Observer locations are shown as black dots on the map. Colors of natural regions in chart and legend are ordered in the same sequence from top to bottom.

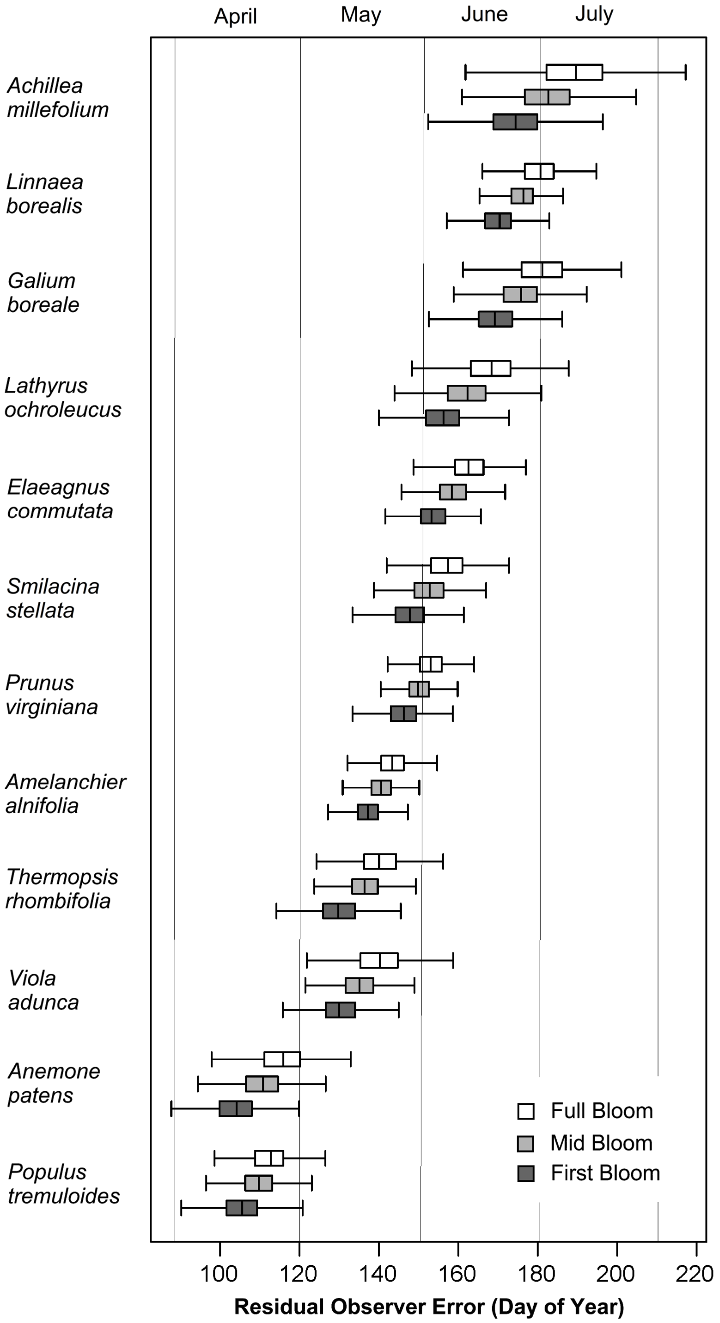

Figure 4-2 Residual error in bloom date (as day of year) for three bloom phases, after interannual variation and variation due to location have been removed through variance partitioning. The center of the boxplots represents the median bloom date and the box encompasses the central 50% of observations.

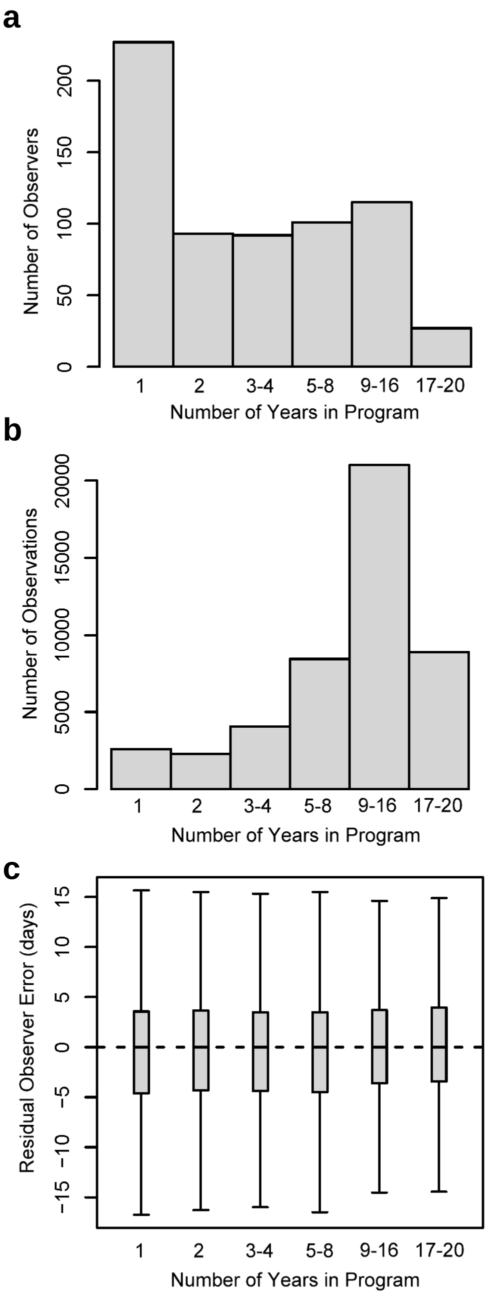

Figure 4-3 Amount and quality of data as a function of length of participation of observers in the program. Histogram of observers by the duration of their participation (a). Total number of data points reported by observers grouped by the duration of their participation (b). Quality of the observation as a function of the duration of their participation, with residual observer error after the effects of year, species, phase, and location (ecosystem) have been removed through variance partitioning **(c).**

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Thesis Synthesis and Conclusions

In this thesis I posed questions about the effects of abiotic drivers on plant phenology and the influence of the urban heat island, and about the effectiveness of the PlantWatch program protocols. In this section I summarize the thesis results and provide answers to the initial research questions.

1) Has the timing of first bloom changed for plant species in Alberta's central parkland between 1936 and 2006? Do changes in phenology relate to global climate change or changes in other abiotic factors?

We found a substantial directional increase of winter and early spring temperatures, with average minimum temperatures in February showing the most pronounced signal (6°C over seven decades). The early-blooming species (*Populus tremuloides* and *Anemone patens*) showed the biggest advance in bloom dates of 14 days over seven decades, representing an advance of 2 days/decade. The later-blooming species' bloom dates advanced between zero and six days.

A predictive heat sum model for first bloom dates explained most of the variation in plant phenology data by observed temperature trends and inter-annual temperature variation. Further analysis showed that other factors including precipitation (rain and snow) and fall chilling (exposure to cool temperatures that leads to winter hardiness) did not contribute significantly to the development timing for these plant species. But plant bloom times have changed faster than thermal time calculations would predict, i.e. the plant response became more sensitive to temperature over the 71 years. The data indicated that minimum temperature may be a better predictor for first bloom than maximum or average temperatures. Because much of the global warming signal is due to pronounced increases in winter and early spring minimum temperatures, this sensitive response could be maladaptive as explained in the next section.

2) Could changes in plant-climate synchronization create potential problems for future plant survival?

The risk of frost damage to plants in early spring is increasing in central Alberta, as the timing of last frost is shifting at a slower rate than the plant response over seven decades. The timing of bloom of the herbaceous *Anemone patens* and woody *Populus tremuloides* occurred increasingly in periods of frosts below -10°C. Of the plant species analysed, these two appear to be the most vulnerable to climate change trends with respect to plant-climate synchronization.

This documentation of shifts in spring vegetation response to warming adds to other evidence of forest changes in the Central Parkland. A large proportion of drought-sensitive tree species have died in response to dry years beginning in 1998: *Populus balsalmifera* (balsalm poplar), *Betula papyrifera* (birch) and *Picea glauca* (white spruce) but also the hardier *Populus tremuloides* (Michaelian et al. 2011). This increasing drought in the grassland-forest ecotone may lead to habitats more suitable for grasses than trees (Henderson and Thorpe 2010).

The ecological implications of shifts in flowering time are numerous (Walther et al. 2002). Phenological mismatches can cause negative consequences for fitness and survival in spring trophic interactions (Kudo et al. 2004, Hegland et al. 2008). Partnerships of plants with pollinators can be impacted if the spring sequence of flower bloom appearances spreads out to the point where gaps in nectar availability occur (Post et al. 2008). Plant pollinators such as bees depend on a continual supply of nectar and pollen from flowers over their active spring and summer season. If start-of-spring plant species such as *P. tremuloides* and *A. patens* are now blooming much earlier while species that bloom in mid-spring such as *Amelanchier alnifolia* (saskatoon) and *Prunus virginiana* (chokecherry) are blooming only slightly earlier, there may now be increasingly ‘lean’ periods for insect pollinators. With lengthening growing seasons there may also be nectar gaps at the end of summer, with ideal weather for insects but with the majority of native plant blooming finished.

3) How much has the urban heat island of Edmonton in central Alberta contributed to earlier blooming in the city as compared to the surrounding rural area? What is the contribution of this urban heat island to the general climate warming signal?

A potential confounding factor in analyzing effects of climate change on bloom times is an increasing heat island effect due to population growth in urban areas where many of the phenology observations are obtained. Some phenological studies have incorporated urban data without analysis of urban-rural differences (Beaubien and Freeland 2000, Luo et al. 2007), or reported on a European rural landscape which is so similar to urban areas that little heat island effect on phenology can be seen (Jochner et al. 2012). This data offered a unique opportunity to disentangle the effects of global climate trends, and urban climate trends caused by increasing population growth.

We could identify a heat island effect in both weather station data and phenology data. Starting in the late 1960’s, temperatures in the month of January showed the greatest increase in urban-rural differences (city warmer than rural). In response to the higher city temperatures, five plant species showed significant earlier blooming than their rural counterparts by 1.7 to 4.5 days, with *Populus tremuloides* showing the biggest differences. Comparing bloom dates from the recent decades of 1987-2006 to the historic 1936-1961 period, we determined the proportion of the overall warming effect that is attributable to an increasing heat island effect (due to city growth) rather than to climate warming. Based on the mean differences in bloom time of seven plant species, 36% of the observed warming signal in Edmonton was due to the heat island effect. Spatial interpolation of the 1987-2006 plant phenology data revealed an urban heat island effect for *P. tremuloides* and *A. alnifolia*.

4) With the goal of guiding the development of better and more robust observer protocols for the Canada PlantWatch program and similar efforts elsewhere, I answered a number of questions related to data quality from volunteer phenology observer networks:

Which are the best plant species to track the effects of climate change, and which bloom phases should be reported to obtain the most accurate bloom times? Better quality data might be expected for plant species which are abundant and widespread, lack similar-looking species, have conspicuous flowers, and have a short blooming period in spring. A number of species have several of these desirable attributes and also show low intra-annual variability in bloom dates. These species were *Anemone patens*, *Populus tremuloides, Amelanchier alnifolia, Prunus virginiana*, and *Elaeagnus commutata.* The phases first and mid bloom were found to have no significant difference in variability.

Does the supplementary microhabitat data gathered by the Alberta PlantWatch program (e.g. location slope and aspect, distance to buildings, etc.) improve the accuracy of observations? An analysis of micro-environmental data including slope and aspect revealed no significant effect on bloom dates at a provincial scale. A more detailed analysis at a larger (ecoregion) scale may reveal different results.

Finally, do experienced long-term observers provide better data (i.e. data that correlate better with climatic factors) than short term observers? The analysis showed that the data from experienced observers showed slightly less variation, but that even data from one-time reporters was precise and valuable.

Thanks to the participation of about 650 individual observers over 20 years, the Alberta PlantWatch program gathered 47000 records for 25 plant species. The benefit of harnessing the skills and energy of volunteers is that as “eyes of science”, they can provide information on the environment over a wide area. Observers showed considerable fidelity to PlantWatch; more than half of the data were from observers who stayed with the program for a decade or more. Such committed volunteers can actually be preferable to paid technicians, as they are often more careful, mature, and will participate for many years (Droege 2007).

These long-term, observer-gathered phenological data may provide some of the best tools to understand the effects of climate changes. The results of experiments with artificial warming do not agree with the results using long term phenology data; in fact they greatly underestimate how much plants change their leafing and flowering phenology with warming (Wolkovich et al. 2012). While there is huge interest from the remote sensing community in correlating satellite measures of green-up with ground-based phenological observations, the results are still very inconsistent (Schwartz and Hanes 2009, White et al. 2009). Thus the expansion of citizen science programs like PlantWatch is essential. Henderson and Thorpe (2010, p. 98) note that for climate change: "One important practical adaptation measure will be effective environmental and ecological monitoring…. Programs like PlantWatch, which tracks the effects that climate variability and trends have on wild vegetation, will be invaluable. Resulting data can provide an index of the expected and realized impacts of shifts in climate".

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