

**Phenology trends covering the periods 1936–1961 and 1987–2021 across
different ecoregions of Alberta, Canada**

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Abstract

Phenology is the study of cyclical patterns of behavior or changes in animals and plants. These cycles are driven by genetic and environmental cues. For plants, weather and environmental conditions such as seasonal temperature changes are the primary drivers of phenology. As such, global climate change can have a direct impact on phenology, and this thesis investigates how vegetation of different ecoregions has responded to directional climate change observed over the past decades. In Alberta, spring phenology of several plant species has been monitored for over 85 years by a citizen science network, Alberta PlantWatch. This thesis evaluates new data that has been added between 2007 and 2021. The study compares trends in 9 species and 4 ecological regions of Alberta, comprising time series at 1,525 locations. For the period 1987–2021, we found a trend towards later bloom times (opposite to global climate change expectations) with rates of 6 days/decade for early-blooming species (*Populus tremuloides* and *Anemone patens*) in the Rocky Mountain Foothill ecoregion. For mid- and late-blooming species and other ecological regions, the typical trends range from 0–3 days per decade towards later bloom times. This 35-year trend (1987–2021) stands in contrast with a long-term trend analysis for one ecoregion (Central Alberta Parklands), where data is available for an 86-year period (1936–2021). Here, bloom times are advancing overall to earlier dates, with the highest rates also observed in *P. tremuloides* and *A. patens* (–1.6 days/decade), representing a 14-day advance over 86 years. The bloom time for mid- and late blooming species remains largely unchanged over this period. The research highlights the importance of a long time series perspective, when evaluating directional climate change trends and their effects on biological systems.

1. Introduction

As defined by Lieth (1974) plant phenology describes the life cycle of plants in their temporal occurrence through the year. Phenology is the study of biological phenomena of cyclical changes in animal or plants which are affected by environmental cues, especially by weather and environmental conditions such as periodic temperature changes. A study of Walther et al. (2002) suggested that climate warming in the past 30 years had a significant impact on the interaction between the timing of plant development stages and those species' distribution across latitude and elevation. Similarly, Parmesan & Yohe (2003) concluded that recent climate warming is closely related to resulting plant phenological changes. They believe that the phenological record provides good documentation in the context of climate change and climate change prediction as a “diagnostic fingerprint”.

In recent years, the study of phenology has received increasing attention because shifts in phenology are considered independent evidence of global climate change. Generally, spring phenology has advanced towards earlier bloom dates at mid and high latitudes, although most studies also show significant regional variability (e.g., Fu et al., 2014), reflecting regional and seasonal differences in the rate of warming. Variability in trends could potentially be observed within Alberta, which comprises diverse ecosystems over a wide range of latitude and elevation. Its six major natural regions (Boreal Forest, Southern Grasslands, Central Parklands, Foothills, Rocky Mountains, and Canadian Shield) are characterized by different landforms, hydrology, geology, soils, vegetation, and climate.

This thesis analyzes spring flowering data in Alberta from 1936 to 2006 to reveal trends in early- to late-blooming species, and across four major natural regions for which we have sufficient data

(Boreal Forest, Southern Grasslands, Central Parklands, Foothills, Rocky Mountains). Building on previous reports (Beaubien and Hamann, 2011a, 2011b), this study presents new data for the most recent 15 years (2007 to 2021) from a citizen science network, Plantwatch Alberta.

Volunteer observers report bloom and leafing stages for up to 26 plant species in over the last 20 years, although long-term time series for up to 86 years are available for only 9 species.

Volunteer observers are asked to tag plants to create time series over multiple years, and report data that include date of bloom, bloom phase (first, mid, late), date of leaf-out, location, and a number of location attributes (near buildings, aspect, slope).

Previous research reports that evaluated on the phenology observations from the Plantwatch Alberta network (Beaubien and Hamann, 2011a, 2011b) reported phenology trends up to the year 2006, and only observations from the Central Parklands of Alberta were included in the analysis.

Here, we expand the analysis to four additional ecoregions, and report a results from an additional 15 years of observations (2007–2021). The objectives of this research are to (1) update the trend-analysis for early-, mid- and late-blooming species; and (2) to investigate of flowering dates and the magnitude of trends in bloom times differ among natural regions, serving as independent evidence of how global climate change may have affected different ecological regions of Alberta.

2. Literature Review

2.1. *Plant Spring Phenology*

Phenology is the study of the timing of life-history events (Fenner 1998), which describes the natural phenomenon of that the life cycle of organisms are affected by the variation in the genetic factors and surrounding environment. The changes like winter stress, water stress, etc. in the life cycle of plants affect the germination, leaf spreading, flowering, leaf discoloration and defoliation, etc., and those changes are occurred on an annual basis. Changes in phenology is considered as the indicators of the changes in climatic and natural environmental factors and are further considered as important indicators of changes in climate and natural environment. Global climate and environment have changed significantly since the 20th century, majorly shown as long-term global warming and anthropogenic habitat alteration. Plant phenology is sensitive to changes in external environment conditions, and the changes in abiotic condition caused by global warming has played a major role in the external drivers of the shifts in plants life cycle.

2.1.1 *Phenology control: heat sum requirements for forcing*

Heat sum is the most direct driver of spring phenology in perennial plants, with adequate heat accumulation needed to break the dormancy and to initiate spring development. Air temperature is a driver which is involved in almost all the physiological and development processes in plant's life cycle. Many studies have shown that increased temperature promote the plant development and facilitate faster transition to the later development stages. Researchers suggested that increased temperature promotes the activity of leave enzymes, thereby accelerating plant growth through alternating the activities of photosynthesis related enzyme (e.g. RUBISCO) in plant

leaves (Bernacchi *et al.* 2001; Walker *et al.* 2013; Moore *et al.* 2021). As the air temperature increases, the heat sum accumulated over time increases substantially. Thus, air temperature during development directly affects the dormancy state of seeds and the flowering time of various plants, as both events are usually tightly related to the heat sum. In various studies, the effect of heat accumulation is proved stronger than chilling, especially in cold regions, chilling effect is explained later in the thesis.

Guo *et al.* (2014) assessed the flowering in temperate fruit trees in Beijing, China and conclude that heat accumulation as the major determiner of flowering, and the effect of chilling on studies trees are minimal. Chmielewski and Rötzer (2001) found that, the variation in the time of phenology in events including budding, leafing and flowering in Europe during 1969 and 1998 is mainly temperature-induced. Similar effect of heat accumulation is also supported by a study on the flowering of British plants (Fitter & Fitter 2002). When studying the impact of temperature and heat on plant development, temperature/ heat is usually quantified as degree-days or degree-hours above a defined base/ threshold temperature which is considered effective enough for initiating plant development (Strand 1987). The base temperature for a specific species is usually assumed as a fixed value in most studies. For example, Moot *et al.* (2000) examine the germination of and emergence of 10 temperate pasture species in New Zealand and found all of those species had a base temperature of ≤ 4 °C. Hanninen (1995) found that a base temperature of > 5 °C can initiate budburst in Douglas-fir. However, due to the variation in location and environmental conditions, a constant base temperature associate with a phenology event is nearly impossible to define in reality (Boyer 1973).

2.1.2 Phenology control: chilling requirements

For woody plants, winter dormancy is a crucial adaptation which prevents the over-early spring development under unfavorable condition. There are two types of dormancies occur during winter: endo-dormancy and eco-dormancy. Endo-dormancy happens when the development of plant is inhibited by the internal factors even under an ideal growing condition, while under eco-dormancy, the ontogenic development is ready but still inhibited by the external unfavorable environmental conditions. Endo-dormancy always comes first, and it is induced by the winter thawing and reduced day length. In order to relieve plants from endo-dormancy state, the exposure to a period of chilling temperature is necessary (Cooke, Eriksson & Junttila 2012). Chilling is a period of low temperature required before budburst. A chilling temperature ranges from 0°C to 10°C in northern deciduous trees (or 4-8°C in boreal and temperate plants (Jewaria *et al.* 2021)) is required for plant to receive signal of the end of winter thawing and the potential of freeze injury.

Chilling is important because it protects the plant from responding to the warming spells during winter and also from the fatal damage from early-spring freezes (Rinne *et al.* 1997; Körner & Basler 2010). After the accumulation of chilling requirement, plants enter the phase of eco-dormancy where the phenology development is directly related to increasing temperature (Chuine 2000). A declining trend of chilling has been observed in previous studies and it is expected to continue in the future, which is considered problematic for species which are dependent on chilling for early season competition (Luedeling *et al.* 2013). The reduced intensity and duration of chilling temperatures caused by climate warming increases the time to reach plant's chilling requirement and makes it harder for plants to reach the threshold temperature, which delays spring development. (Murray, Cannell & Smith 1989b). According to

Man et al. (2020), slightly insufficient chilling delays budburst of temperate tree species in Ontario, while severe insufficiency leads to abnormalities in flush and reduction in leaf/shoot expansion. Similar delay in the timing of budburst due to chilling is also found in other studies (Murray, Cannell & Smith 1989a; Heide 1993; Cleland *et al.* 2007). The advancing effect of chilling is supported by Nanninga et al. (2017), who showed that the bud break of tested temperate deciduous species significantly advanced with increased chilling exposure.

The relationship between chilling and heat requirement is quite complex and differs among species. As mentioned in the previous part, warmer temperature during heat accumulation contribute to the heat sum towards budburst, however, if the warming occurs during chilling accumulation, it has the opposite effect. As suggested by previous study by Cannell and Smith (1986), if the chilling requirement is reached before the warming, as observed with apple blossom (*Malus pumila*) in Kent, where the time of thermal requirement to reach budburst is not altered by warming, then the following budburst will occur earlier with increasing spring temperature. However, due to the climate warming, the chilling accumulation and heat accumulation periods have become less clearly delineated. Especially in the cold regions with high level of winter chilling, the major driver of phenology is no longer solely heat accumulation (forcing) but the interaction of chilling and forcing (Noorazar *et al.* 2022). Kaufmann and Blanke (2019) suggest that the climate warming-induced insufficiency in chilling requirement can be compensated by more forcing in sweet cherry by up to 50%, similar compensation effect of warming heat accumulation is also observed in the dormancy release in Douglas-fir (Harrington, Gould & St.Clair 2010). Sufficient chilling can also result in reduced time to reach heat requirement. In general, plants are observed with greater development rate, less time to reach certain development stages and reduction of time between phenology events under warmer

temperature after increased duration of chilling (Cannell & Smith 1983; Cannell 1989; Cannell 1997).

2.1.3 Phenology control: secondary drivers

Photoperiod is another cue which controls the spring phenology. Cook et al. (2012) suggests that in the past observational studies which include increasing temperature as primary cue of spring phenology, the covariates like extended daylight and chilling are hard to remove completely. In order to investigate the photoperiod effect on phenology, Caffarra & Donnelly (2011) conduct the controlled experiment and find that when photoperiod is presented as the sole variable, the promoting effect on budburst is observed, this found is also supported by other researchers that longer photoperiod can lead to advanced budburst and leafout date in temperate woody species (Flynn & Wolkovich 2018). Fu et al. (2019) point out that shorter photoperiod prevents advanced leaf-out in *Fagus sylvatica* as the temperature sensitivity is significantly reduced by shorter daylight, and therefore more time for heat accumulation is required to break the dormancy. More studies highlight the importance of the complex interaction between chilling and photoperiod in promoting budburst and releasing dormancy (Chuine 2000; Caffarra & Donnelly 2011). Higher percentage of budburst is presented with extended photoperiod during chilling period among four tree species (*T. cordata*, *F. sylvatica*, *B. pubescens* and *S. x smithiana*), while intraspecific variation in increased budburst rate is shown based on different adaptation strategies of tested species (Caffarra & Donnelly 2011).

Soil moisture is an important determiner of plant growth. The specific soil moisture in a site is due to a suite of factors like precipitation, evapotranspiration, and soil properties (Moore *et al.* 2015). Soil moisture is contributed by the water from precipitation or irrigation. After a

considerable amount of water is evaporated into atmosphere, the remaining soil moisture directly impacts plant development. As suggested by Tao et al (2021), effects of soil moisture on phenology is stronger in dry condition with the long-term low water availability. The underground root competition over limited water is one of the biggest constraints of plant development in water-limited condition (Burke *et al.* 1998), which makes soil water content a determinate factor of phenology in arid or semiarid area. As suggested by Luo et al. (2021), a negative correlation is found between the spring soil moisture and the start date of the season in the Mongolian Plateau, which indicates the advancing of the spring under arid conditions. Similar findings is supported by the study of Yuan et al. (2007), the earlier beginning of development is observed in two herbaceous species in a semi-arid steppe ecosystem.

Circadian rhythm contains the internal biological timekeeping mechanism in plant which anticipates the changes in surrounding environment in an annual basis, which is also described as the internal clock of plant. Under natural environment, the synchronization of circadian rhythm is triggered by the changes in the environmental cues, and its complex interaction with environmental cues and other drivers furthermore underlie the phenology development. As claimed by Srivastava et al. (2019), circadian rhythm is one of the ultimate controls of flowering time which in contributed by varies of circadian clock-regulated genes. The most dependent and reliable cue of circadian rhythm are the photoperiod and temperature variation during the year, which is aligned with what is mentioned earlier that extended day length provide plant with signals of the timing of seasons (Kreitzman & Foster 2010; Nelson, Denlinger & Somers 2010).

2.2. Spring phenology models

Phenology model is used to predict the timing of the phenological events during plant development and to quantify the effect of climate change on plant's life cycle. Plant phenology is a significant regulator of the ecosystem function, feedback and productivity under different climate systems (Richardson *et al.* 2012; Richardson *et al.* 2013), thus, the phenology model which describes the phenology-climate interaction is considered as a key component in predicting the impact of climate change on plant development and future yield (Fu *et al.* 2014; Chuine & Régnière 2017). Thermal time model is used to predict the impact of temperature as the key factor on plant phenology development (Mkhabela *et al.* 2016). In this approach, a linear relationship between plant development and temperature is assumed after a threshold temperature is met (Bonhomme 2000; Saiyed *et al.* 2009). Therefore, Plant development is considered as the response of the accumulation of the defined thermal unit (Cannell & Smith 1983), and the timing of budburst is predicted accordingly. Thermal time model simplifies the modeling process by including thermal unit as the only factor, which allows the implementation of broad-scale and more unified prediction across larger region and range of species (Liang & Wu 2021). In addition, thermal time model is also proved with adequate accuracy for the examination of the budburst date from the long-term phenology data by several studies (Hannerz 1999; Linkosalo 2000; Bailey & Harrington 2006). However, thermal time is considered as a quite vague concept because the use of methodologies and the selection of measurement unit are largely case-specific (Parent, Millet & Tardieu 2018). For example, growing degree day (GDD) is the most commonly used thermal unit which measures the daily mean temperature with a base temperature (Shaykewich 1995), while physiological day (Pday) (Sands, Hackett & Nix 1979),

biological days (Hunt & Pararajasingham 1995), etc. are also used as thermal units in previous studies with different measurement and underlined definition (Parent, Millet & Tardieu 2018).

2.2.1 Heat accumulation model: growing degree days

Growing degree day (GDD) is the unit used for the estimation of plant growth and development during the growing season using the measurement of heat accumulation. When using GDD as the variable of measurement, the cues of phenology event is simplified with the daily air temperature is considered as the major factor of phenological development under the normal condition. Three variables are considered in GDD algorithm, which are daily maximum temperature (T_{\max}), daily minimum temperature (T_{\min}) and the base temperature (T_{base}). The daily mean air temperature (T_{mean}) is calculated from T_{\max} and T_{\min} , and the T_{mean} over a base temperature (T_{base}) is accumulated over time in a daily basis. The base temperature selected is mostly case-specific, it describes a specific threshold temperature, and the development of plant is inhibited until the temperature is reached. The selection of base temperature is largely based on the variation in the thermal requirement across locations, which even presented with same species in the same study. In addition, the base temperature is also the parameter which determines the start and the end of the season. According to the GDD products released by Agriculture and Agri-Food Canada (2017), the base temperature varies from 0 to 15°C. Sallenave et al. (2021) concluded that, the selection of base temperature affect the accuracy of the prediction on seedling emergence of bermudagrasses, a base temperature of 15°C explains the seedling emergence better than the base temperature of 5°C in the field setting. The different thermal requirement of plants are reflected by the variation in GDD, the common species with less thermal requirement include red maple, star magnolia, Rhododendron, etc., which requires as few as 1-49 GDD to reach first bloom in

March to early April, while other species like *Clematis paniculata* or *Euonymus alata* may need up to 1999 GDD to reach first bloom in August.

2.2.2 Chilling requirement models: chilling hours

Chill hour is the parameter of determine the chilling requirement for plant development. As mentioned in the previous section, the lack in chilling may result in the delay or even absence in the spring phenology event, while the chill hours helps to keep the track of how much chilling requirement is met. Chill hour is defined as the hour of exposure in chilling temperature of below 7.2°C or 45°F during the dormant season, as according to Jagannathan et al. (2020) the dormant season for temperate crop species in California range from the very beginning of November to the end of February. Weinberger (1950) developed the accumulated chilling hour model which is named Weinberger Model, this model is highly dependent on the hourly temperature measurement. Any temperature between 0°C to 7.2°C is assumed with a chilling effect on plant phenology, and each hour of which the temperature fell in-between this threshold range is counted for one chilling hour, and the chilling hour before the releasing of plant dormancy are accumulated to meet the chilling requirement (Luedeling 2012).

2.2.3 Chilling requirement models: Utah model

Utah model is a more complex model of estimating the chilling requirement. Unlike the Weinberger Model, Utah model is a weighted model which assigns different chilling efficiencies to different temperature ranges (Richardson *et al.* 1974). It also introduces the concept of negative chilling accumulation, which is also called chilling negation. The optimum temperature for chilling accumulation is 2.5-12.5°C (Ramjan 2019), while each hour which contains a

temperature of over 15.9°C is accumulated as a negative chill unit which can reverse the chill units accumulated previously (Richardson *et al.* 1974).

2.2.4 Chilling requirement models: dynamic model

A two-step process is involved in the dynamic model designed by Erez *et al.* (1979). First, an irreversible intermediate product which requires chill accumulation is produced through the exposure to chilling temperature ranges from 0°C to 7.2°C. The chill accumulation during the production of intermediate product is irreversible, which means that, it can be either promoted by moderate temperature or destroyed by the exposure to high temperature (Eike, Minghua & Evan 2009). After enough winter chill is accumulated, this intermediate product is converted into the chill unit, which named Chill Portion. The Chill Portion is no longer irreversible and can be safely banked for reach the chilling requirement.

2.3. Climate change and phenology trends

2.3.1 Global review of phenology studies

The shift in plant phenology directly manifests climate change, especially climate warming. Advanced spring phenology has been observed and recorded across countries in the north hemisphere (Walther *et al.* 2002; Menzel *et al.* 2006), which is considered coherent with advanced timing of spring season (Root *et al.* 2003). Menzel *et al.* (2006) studied data of 542 species in Europe and found advanced trend in 70% of the flowering, leafing and fruiting data from 1971 to 2000. The rate of advance was affected by factors like region, temperature variability, plant's temperature sensitivity, pollination, etc. Similar trends in phenology

advancing is also found in North America, 93% of the species in the experimental study by Rice et al. (2018) show accelerated leaf unfolding with a wide-spread range of 0.8–6.4 days in +1.7°C warming and 1.0–12.7 days in +3.4°C warming. In the same study, 78% of the species show advanced flowering with warming with an average range of 1.5 ± 2.2 days in +1.7°C and 1.8 ± 2.1 days in +3.4°C warming. The shift in flower leaf sequence (FLS) is observed in multiple species, and the specific FLS may be considered as the evolutionary consequence of the environmental adaptation for those flowering-first woody plant species (Rathcke & Lacey 1985). As suggested by Ma et al. (2021), longer time interval during flowering and leafing is observed in four European tree species with a range of prolonged interval of 0.6-1.3 days per decade from 1950 to 2013 (Ma *et al.* 2021). The shift in timing of phenological event is beneficial to some species while it also exposes other species in the great risk of reducing fitness, for example, Inouye (2008) suggests that plants are more likely to experience frost damage under phenological advancement if the temperature in early spring does not meet the requirement of development. When the time of the last frost remains fixed and the flowering is advanced, or the last frost is advanced at a slower rate than early phenological event, higher probability of frost damage is proposed (Beaubien and Hamann, 2011a). This suggestion is supported by the studies by Fitchett et al. (2014) that a lag in the rate of frost date advancement is observed in Kerman and Shiraz, Iran, which increase the risk of frost damage to citrus flowering.

2.3.2 Phenology trends in Alberta

Since greenhouse gases heat up the lower atmosphere, rising temperature is considered as a key indicator of the greenhouse gas emission induced climate change in Alberta due to Alberta's high greenhouse gas emission contributed by the fossil fuel industry. Within Alberta, the study on the

effect of climate change on plant phenology mostly focuses on the spring flowering phenology of common wildflowers across the province. As the baseline study of this thesis, Beaubien and Hamann (2011) examined spring flowering time of seven common wildflower species in Alberta and found that advancing trends are observed in the first bloom date of all tested species from 1936 to 2006, which is aligned with the warming trend over the same duration. They evaluated the climate trend and bloom times in central Alberta and found that the lag in late spring frost advancement exposes higher frost risk for early spring-blooming species. By examining the long-term first bloom data of aspen poplar in Edmonton, Alberta from 1900 to 1997, an advance of 2.7 days per decade is reported (Beaubien & Freeland 2000).

2.4. Citizen-science phenology networks

Citizen science has been developed rapidly in the global scientific community during the past decades. In the recent research, citizen science is most widely utilized in the fields of conservation, biodiversity and climate change, with the studies on migratory birds and butterflies being the most popular. In general, citizen science is an organized scientific activity where the participation of the public is involved. For studies which biological observations are required, such as phenology, the involving of citizen science is more favored mainly by the fact that they usually cover a larger spatial and temporal scale but can also be converted to small-scale research. In recent years, citizen science has flourished due to the development of the Internet. Some study suggested that the recent increase in citizen science is the result of the integration of ecology and information science (Lukyanenko, Wiggins & Rosser 2020). Through this combination, the efficiency and convenience of data collection, processing, and visualization

have been greatly enhanced, and internet technology makes the participation of wide range of volunteers in the same study possible. The traditional scientific process is that researchers define problems based on existing knowledge or conjectures, and then observe and propose hypotheses and further design and test the hypotheses. Under such a concept, non-experimental observations are often considered lacking in accuracy and unscientific, whereas local or regional intensive studies may not be sufficient to understand overall ecological processes. One of the strengths of citizen science in the biological field is the promotion of natural history observations over time and over larger spatial scales which brings new insights to ecological research under proper practices. Studies on the distribution and quantity of species, and their interactions with the surrounding environment are major characteristics of ecology research. Citizen science has been widely used to understand the distribution of species, and its mechanisms can also be explored using citizen science data. Associations with habitats are the type of studies for which bio-distribution data are most frequently applied. At present, many large-scale or global-scale environmental information such as global forest distribution, climate status, etc., can be collected through technologies like telemetry, but whether species appear in specific locations or specific biological events still needs direct observations. At the same time, by participating, citizen scientists get an opportunity to learn about the field research techniques and get more involved in scientific processes. This creates greater public awareness of the climate issue.

Citizen science has contributed to the large-scale knowledge and understanding of phenology in a global scale through providing tremendous data for quantifying the impact of climate change on phenology (Ramaswami, Sidhu & Quader 2021). A great dependence on the intensive long-term data collection from limited locations and on limited species by specific group of researchers is presented in some studies.

The use of data collected from citizen science program is sometimes criticized for the poor data quality, and the control and assessing of volunteer-collected data is also a focus for those studies where citizen science is implemented. As suggested by Beaubien and Hamann (2011b), if volunteer citizen scientists are properly trained in species identification and phenophase recognition, and have gained experience in years of participation, the quality of data collection can be considerably high. Long-term involvement of citizen scientists may contribute to convenience in trend analysis, but the precision of data collected from short-term observer and long-term observer are similar and both largely unbiased. The quality of data acquisition from citizen scientists is dependent more on factors like training, study design, communication skill of researchers, analytical methodology and volunteers' willingness, than solely the effect of volunteer involvement (Schmeller *et al.* 2009).

3. Methods

3.1. Alberta PlantWatch observation protocols

The first phenology data in Alberta goes back to 1936 with the major purpose of monitoring agricultural activities. While the data from 1936 to 1961 used in this thesis was collected by the previous program run by Agriculture Canada (Russell, 1962). During the 26 years of running this program, the spring blooming time of 30 native plant species has been recorded. A later phenology program by Bird (1983) was initiated in 1973 and Beaubien extended it in 1987, while the methodology for spring phenology tracking and data acquisition has remained unchanged. Alberta PlantWatch program recruits volunteers across the province of Alberta and asks volunteers to report the location, timing, and environmental conditions of spring phenology

events of up to 26 common plant species. In this program, volunteer-collected data is utilized to understand how vegetation responds to climate change, which further helps predict future phenology shifts in locations of plant occurrence.

More than 1000 observers have been involved in this program, contributing to more than 60,000 observations since the initiation. Up to 300 observers are reported each year; however, in recent years, the involvement of observers has slightly declined. In 2021, observation data from more than 50 long-term volunteer observers were collected, which has contributed to more than 740 observation records and provides valuable data for the phenology trend analysis for this thesis. The observation data of 26 shrub and woody species are collected in this study (Table 1). The selection of plant species is based on several criteria: wide distribution in Alberta, lack of similar species, relatively short bloom period in spring, and the convenience of identification by volunteers. The description and the protocol of observation can be found on the Alberta PlantWatch website (<https://plantwatch.naturealberta.ca/>)

In this study, the dates of the first bloom, mid-bloom, full bloom and leaf out of a series of common plant species in Alberta are observed and evaluated. The first bloom is the date when the first flowers on the observed tree open. For shrubs, non-woody plants, and tree species, flowers should occur in at least three different locations on the individual plant; Mid bloom is defined as the stage when about half (50%) of flower buds open; full bloom is recorded when approximately 90% of flowers open; leaf out is defined as when first leaves unfurled in at least three places on tree or shrub. The observations are required to be obtained from locations with normal heat conditions and relatively flat topography, which can minimize the variation and bias caused by point heat sources of human activities and unique terrain. For observers to select which plants to observe, they were requested to select plants which reflect the average bloom

time of the species in that area. Thus, the data collected from observers represent the average bloom time in the study area, and outliers like the earliest bloom time are eliminated in the study.

The mean date of bud break is utilized to quantify the changes in the phenology time.

Table 1. Common and scientific name of plant species observed in Alberta PlantWatch network (1987 to 2021) and prior records (1936 to 1961). Number of observation statistics apply to the period 1987 to 2021 only.

Common Name	Scientific name	Start year	End year	Number of observations	Mean n. obs. per year
Aspen Poplar	<i>Populus tremuloides</i>	1936	2021	850	25
Prairie Crocus	<i>Anemone patens</i>	1936	2021	810	24
Balsam Poplar	<i>Populus balsamifera</i>	1987	2021	190	6
Bearberry	<i>Arctostaphylos uva-ursi</i>	1987	2021	380	11
Larch (Tamarack)	<i>Larix laricina</i>	1987	2021	325	10
Dandelion	<i>Taraxacum officinale</i>	1987	2021	510	15
Paper Birch	<i>Betula papyrifera</i>	1987	2021	175	5
Early Blue Violet	<i>Viola adunca</i>	1936	2021	870	26
Lodgepole Pine	<i>Pinus contorta</i>	1987	2021	295	9
Golden Bean	<i>Thermopsis rhombifolia</i>	1987	2021	770	22
Wild Strawberry	<i>Fragaria virginiana/vesca</i>	1987	2021	485	14
Saskatoon	<i>Amelanchier alnifolia</i>	1936	2021	890	26
Star-flowered Solomon's Seal	<i>Maianthemum stellatum</i>	1936	2021	830	24
Choke Cherry	<i>Prunus virginiana</i>	1936	2021	840	25
Wolf Willow	<i>Elaeagnus commutata</i>	1936	2021	825	24
Common Purple Lilac	<i>Syringa vulgaris</i>	1987	2021	590	17
Starflower	<i>Lysimachia borealis</i>	1987	2021	105	3
Lingonberry, Cranberry	<i>Vaccinium vitis-idaea</i>	1987	2021	95	3
Cloudberry	<i>R. chamaemorus</i>	1987	2021	45	1
Bunchberry	<i>Cornus canadensis</i>	1987	2021	405	12
Northern Bedstraw	<i>Galium boreale</i>	1936	2021	860	25
Twinflower	<i>Linnaea borealis</i>	1987	2021	740	22
Labrador Tea	<i>Rhododendron groenlandicum</i>	1987	2021	355	10
Common Yarrow	<i>Achillea millefolium</i>	1936	2021	850	25
Purple Saxifrage	<i>Saxifraga oppositifolia</i>	1987	2021	110	3
White Dryad	<i>Dryas integrifolia/ octopetala</i>	1987	2021	155	5

3.2. Study area

This study highly depends on citizen science, contributing to a tremendous quantity of spring phenology observations across Alberta's natural regions. The entire area of Alberta is divided into six natural regions: Grassland, Parkland, Foothills, Boreal Forest, Rocky Mountains and Canadian Shield. A total of approximately 662,583 km² is covered in this study, which is the area of the province of Alberta. Natural regions are the largest ecological units in the ecological spatial classification system, which provide general information about Alberta's landscapes. Each region contains landscape patterns characterized by a mix of vegetation, soils and landform features unique from other natural regions. Rocky Mountain natural region contains dramatic landscapes like mountain peaks, glaciers, sloped mountains and streams. The significant variation in climate and terrain in the Rocky Mountain natural region provides a habitat for a wide range of plant species. Foothills natural region is characterized by variable terrain, lower slope, and relatively moist and cool climate, which acts as a transition between Rocky Mountain and other northwest ecosystems. Due to the limitation in precipitation, the Grassland natural region is characterized by shrub and forb coverage, and this region is heavily cultivated. Parkland natural region is the area with the highest coverage of agriculture. A mixture of grassland and shrub species like saskatoon, chokeberry, snowberry, etc. are native species in the area. The Boreal Forest natural region covers the largest area among all-natural regions, and it consists of a combination of upland forests, lowland forests and abundant low-lying wetlands. Canadian Shield contains a relatively flat landscape covered by exposed bedrock and glacier deposits with scattered lakes and wetlands. The observation data is aggregated based on natural regions, and the variation in the bloom and bud break time over the years is compared at a regional level.

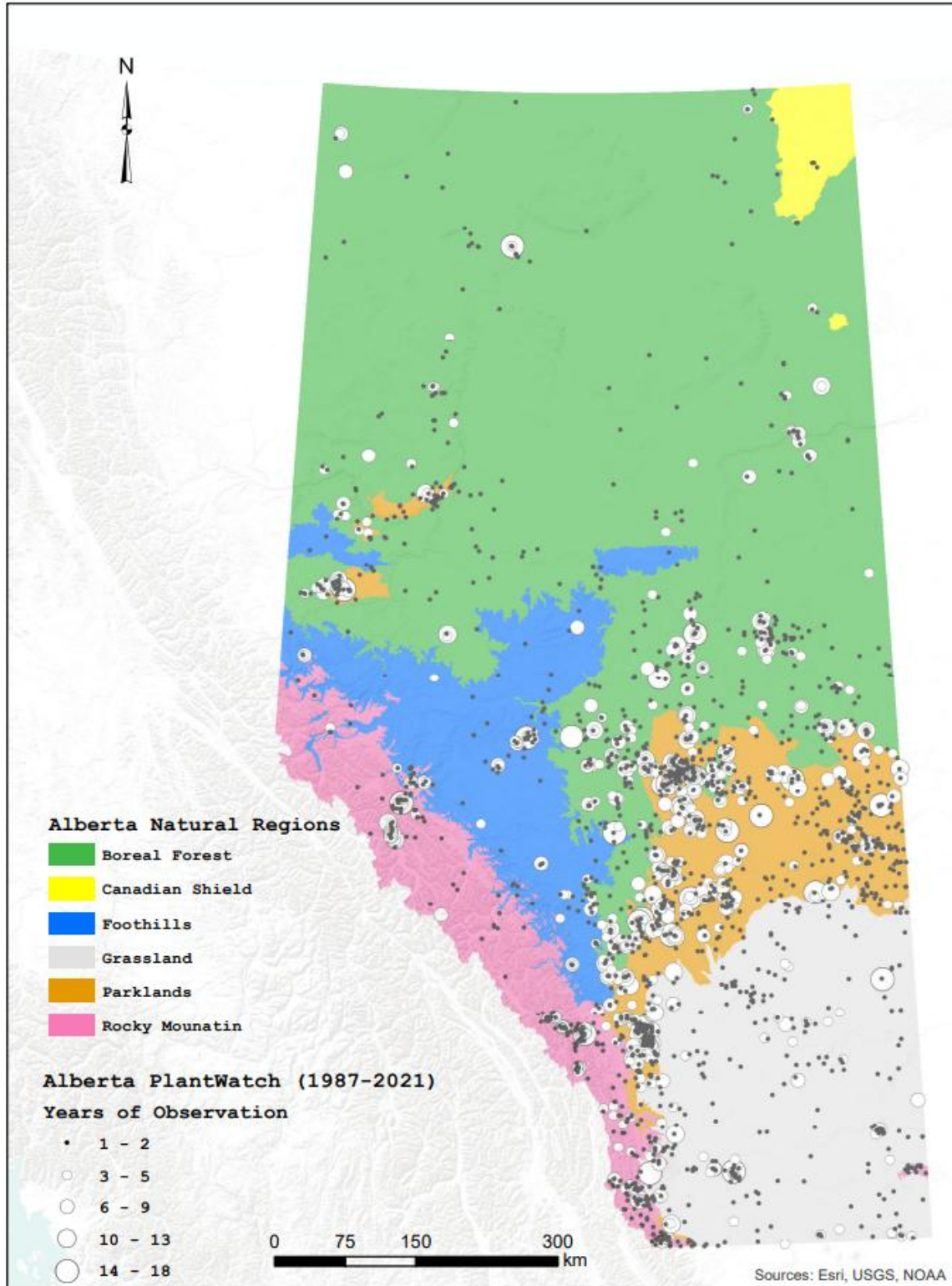


Figure 1. A map depicting the geographic location of the study area by natural regions of Alberta. The location and the number of year of the observation collected from each observation point are indicated using gradual symbol.

3.3. Statistical analysis

Mean date of bloom for each species, year, region, and phenophase were estimated using the *emmeans* function from the *emmeans* package (Lenth, 2019) based on a mixed linear model constructed using *lmer* method from the *lme4* package in R (Bates et al., 2015).

Trends were analyzed from estimated annual means by species and region using simple linear regression model in Excel, where year is the independent variable and blooming time (day of year) is the dependent variable. R-square (coefficient of determination) and p-value are calculated to determine the correlation between variables and the significance of the trend.

4. Results

4.1. Bloom dates by species and region

The average first bloom dates of studied species are analyzed for determining the relative blooming time during the blooming season. *Anemone patens* and *Populus tremuloide* are both early-blooming species which bloom during the early season and their average first bloom time is relatively close, which are the 109th and 110th day of the year. *Viola adunca*, *Amelanchier alnifolia*, *Prunus virginiana* and *Smiliacina stellatum* bloom later during the summer and their bloom date ranges from 132th to 150th day of the year. *Galium boreale* and *Achillea millefolium* are considered late-blooming species, which contain average first bloom time of respectively 173th and 176th day of the year. The variation of blooming time over different natural regions is also observed. In general, ordering the natural regions from where the blooming is observed from

the earliest to the latest, they are: Grassland, Parkland, Foothills, Boreal Forest and Rocky Mountains.

Table 2. The average first bloom date (in day of year) and standard error by species and region.

Species	Grassland	Parklands	Foothills	Boreal Forest	Rocky Mtns	Average
<i>Anemone patens</i>	106 (± 3)	106 (± 1.4)	108 (± 5.5)	110 (± 3)	112 (± 3)	109
<i>Populus tremuloides</i>	108 (± 4)	109 (± 1)	112.5 (± 4)	110 (± 1.4)	113 (± 4)	111
<i>Viola adunca</i>	129 (± 4)	130 (± 1)	133.5 (± 4)	133 (± 1.4)	137 (± 4)	132
<i>Amelanchier alnifolia</i>	134 (± 3)	136 (± 1)	139 (± 4)	136 (± 1.4)	145 (± 3)	138
<i>Prunus virginiana</i>	145 (± 3)	145 (± 1)	148 (± 5)	145 (± 2)	157 (± 5)	148
<i>Smilacina stellatum</i>	144 (± 3)	148 (± 1.5)	158 (± 5)	150 (± 2)	152 (± 3)	150
<i>Elaeagn. commutata</i>	153 (± 3)	153 (± 2)	162 (± 6)	152.5 (± 3)	164 (± 4)	156
<i>Galium boreale</i>	170 (± 4)	169 (± 1.6)	175 (± 4)	169 (± 2)	180 (± 3)	173
<i>Achillea millefolium</i>	171 (± 3)	176 (± 2)	180 (± 4)	17 (± 2)	177.5 (± 3)	176

4.2. Long-term trends for the Parkland ecoregion (1936-present)

In order to demonstrate the long-term phenology, the trends of nine species which are continually surveyed from the initiation of the preceding program (1936) to the present are analyzed in a broader spatial scale. The data collected across Alberta are aggregated for the evaluation of first bloom date and the variation between natural regions are not considered due to the lack of observation location in the data collected from the early program. Due to the suspension of the program between 1962 and 1972, the discontinuity in data is shown in the trend. Among the nine species which demonstrate the long-term trend from 1936 to 2021, the time of first bloom experienced an advance for five out of nine surveyed species from 1936 to 2021, which are *Anemone patens*, *Achillea millefolium*, *Populus tremuloides*, *Prunus virginiana*, and *Elaeagnus commutata*. Early blooming species are experiencing high rate of advancing during the studied period, while the advancing is described using linear relationship, *Anemone*

patens ($p = 0.02$) and *Populus tremuloides* ($p = 0.006$) are both significantly advanced with similar rates of 1.6 days per decade. In contrast, for the mid and late blooming species which bloom later in spring and summer, more variation is shown in the direction of the shift. For those mid blooming species which shows advancing trend over time, the rate of advancing is significantly lower than early blooming species, the rate of *Achillea millefolium*, *Prunus virginiana* and *Elaeagnus commutata* ranges from 0.3 to 0.6 days per decade, while the trends are all insignificant ($p = 0.39, 0.12$ and 0.17). Four out of seven late blooming species have shown a delayed trend in the time of first bloom. *Galium boreale* and *Amelanchier alnifolia* show slight delay over time with a rate of 0.2 day per decade, however, the trends of both species are not significant ($p = 0.51$ and 0.39). While *smilacina stellata* contains the highest rate of delaying which is 0.7 days per decade, *Viola adunca* does not show any accountable fluctuation in first bloom time over year ($p < 0.001$).

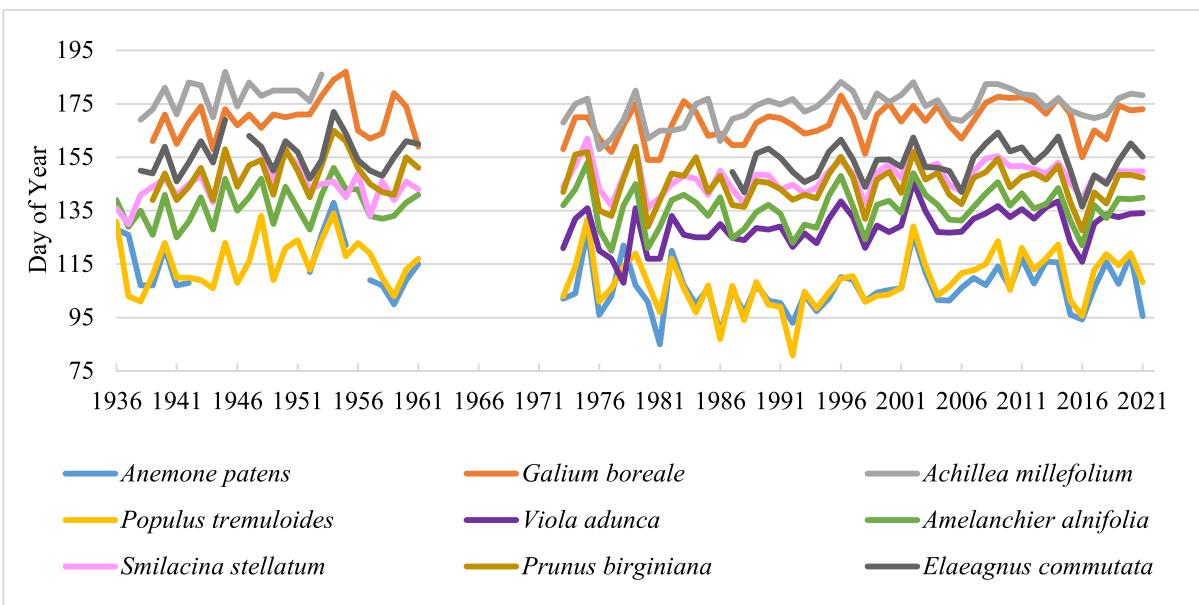


Figure 1. Trends of the shift in first bloom date of species from 1936 to 2021 in day of year.

Table 3. Trends of the shift in first bloom date of studies species from 1936 to 2021 in day of year, the trends are quantified in a day per decade basis.

Species	Change (days/decade)
<i>Anemone patens</i>	-1.6
<i>Populus tremuloides</i>	-1.6
<i>Viola adunca</i>	0
<i>Smilacina stellata</i>	0.7
<i>Amelanchier alnifolia</i>	0.2
<i>Prunus virginiana</i>	-0.5
<i>Elaeagnus commutata</i>	-0.3
<i>Galium boreale</i>	0.2
<i>Achillea millefolium</i>	-0.6

4.3. Medium-term trends by natural regions (1987-present)

Starting from 1987, the observation data are collected with detailed locations, which make it possible for the evaluation and comparison of the variation in regional trends. As shown in Figure 5, the variation in the rate of change for the same species across different natural regions can be significant, for some specific species the variation is demonstrated as divergent shifts (delay/advance). The first bloom of *Anemone patens* in Foothills has experienced a significantly high rate of delaying which reached 6 days per decade, while the rate of delaying is both relatively lower in Grassland and Parkland which are respectively 4 and 2 days per decade. *Populus tremuloides* is the species which shows the most advanced trend in the long-term among all species, however, the advanced trend is not observed during 1987 and 2021, rate of delaying ranges from 3 to 5 days per decade, while the greatest rate of delaying (5 days/decade) is contained by Parklands. Consistent delayed trends are shown in *Viola adunca* with the highest rate in Foothills (3 days/decade) and lowest rate in Grassland (1.6 days/decade). Highest rates of

delaying for *Galium boreale* (3.5 days/decade), and *Prunus virginiana* (6 days/decade) are also shown in Foothills.

Three out of nine studied species have shown advancing trends in specific natural regions, with Rocky Mountain being the major natural region which contains the delaying trends, they are *Elaeagnus commutata*, *Galium boreale* and *Achillea millefolium*. Delayed first bloom is observed in *Elaeagnus commutate*, *Galium boreale* (1 day/decade) and *Achillea millefolium* in Rocky Mountain (1.5 day/decade). Through the paired t-test (Table 5), we found that there is a major difference exists between the trend in Foothills and Boreal Forest (0.44), Boreal Forest and Rocky Mountain (0.55) and Foothills and Grassland (0.29), while no significant difference is observed among other natural regions. This result indicates that the most significant gap in spring phenology trend is observed between Boreal Forest and Rocky Mountain, while the trends in Foothills are inconsistent with the trends in Boreal Forest and Grassland.

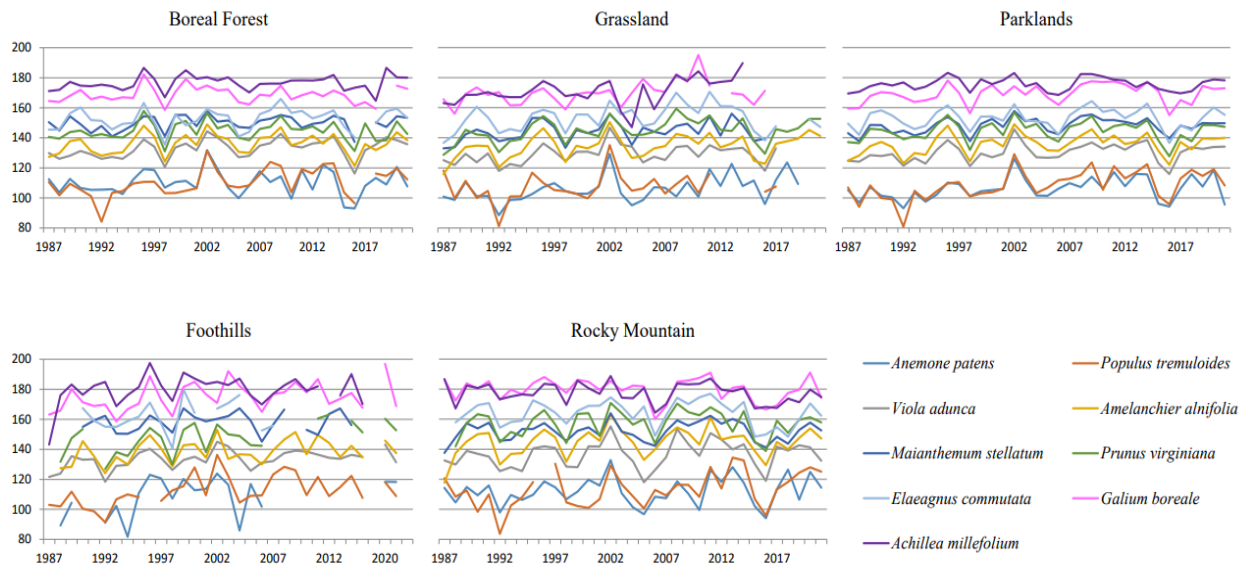


Figure 2. Trends in first bloom date of studies species from 1987 to 2021 in day of year, the trends are categorized based on the natural regions.

Table 4. Trends of the shift in first bloom date of studies species from 1987 to 2021 in day of year, the trends are categorized based on the natural regions and quantified as day per decade.

	Boreal Forest	Foothills	Grassland	Parklands	Rocky Mnts.
<i>Anemone patens</i>	0.1	6.3	3.7	2.2	1.4
<i>Populus tremuloides</i>	4.0	4.6	3.1	4.8	4.5
<i>Viola adunca</i>	2.1	2.8	1.6	1.8	1.8
<i>Amelanchier alnifolia</i>	1.1	2.8	2.8	1.8	2.3
<i>Prunus virginiana</i>	0.2	6.2	2.9	0.7	0.8
<i>Elaeagnus commutata</i>	1.2	-0.1	1.8	0.6	-1.0
<i>Smilacina stellatum</i>	0.8	0.8	2.3	1.4	0.7
<i>Galium boreale</i>	0.0	3.5	2.8	1.7	-1.3
<i>Achillea millefolium</i>	0.8	2.0	3.5	0.3	-1.5
Average	1.1	3.2	2.7	1.7	0.9



Figure 3. Trends of the shift in first bloom date of studies species in different natural regions from 1987 to 2021 in day of year; trend is quantified as day per decade.

Table 5. The result of paired t-test, evaluating significant regional differences among average trends from 1987 to 2021 (Table 4) among different natural regions. P-values significant at an alpha level of 0.05 are highlighted in bold.

	Foothills	Grassland	Parklands	Rocky Mountain
Boreal Forest	0.44	0.02	0.11	0.55
Foothills		0.29	0.05	0.01
Grassland			0.06	0.02
Parklands				0.05

5. Discussion

5.1. Delayed spring phenology in recent year

As mentioned earlier in this thesis, Hamann and Beaubien (2011a) studied the spring phenology in Alberta from 1987 to 2006 and suggested advancing trends. However, after analyzing the more recent spring phenology trend from 1987 to 2021, we found that the first bloom time of studied species has trended later in general, which is inconsistent with the previous studies which suggest earlier spring phenology. Compared with the phenology trend in the regions with similar high latitude in the northern hemisphere, the direction of estimated spring phenology trend in Alberta and the trend suggested by Fu et al. (2014) in western central Europe are divergent. According to the Adjusted and Homogenized Canadian Climate Database (2021), the temperature in Alberta has been constantly inclined during the study period due to climate change. Hamann and Beaubien (2011a) mentioned that the temperature is negatively correlated with the timing of the first bloom in the more limited study area (Central Parkland subregion) between 1936 and 2006 due to the requirement to reach the heatsum. However, combined with

the finding of this thesis, this negative correlation between warming and the earlier first bloom is no longer demonstrated in Alberta during the more recent study period from 1987 to 2021. A similar finding is suggested by Wang et al. (2019), when looking at phenology data from more recent years and larger geographic scale, spring phenology stopped advancing or started delaying during warming conditions.

When looking at the trend on a broader temporal scale, generally advanced spring phenology is observed in specific species from 1936 to 2021, even though most advancing trends do not show much statistical significance except for the *Smilacina stellata* ($p = 0.02$). During the long-term analysis, the most pronounced shift in earlier spring phenology is observed in the earliest blooming species (*Anemone patens* and *Populus tremuloides*) at a similar rate of 1.6 days per decade, in other words, the first bloom date of both species has been advanced for approximately two weeks in 85 years of observation. In contrast, the shift in flowering dates of late-blooming species ranges from -0.6 to 0.2 days per decade. Although a linear relationship reflects the earlier flowering over time for some late-blooming species (*Achillea millefolium* ($p = 0.39$) and *Elaeagnus commutata* ($p = 0.17$)), the trends are not statistically significant and later blooming is observed in 2021 than 1936.

5.2. Trends spring phenology among different natural regions

Different trends in the same species are observed across different natural regions. As mentioned earlier in the thesis, the variability in climate and environment is one of the primary drivers of the shift in spring phenology, the unique combination of environmental components in each natural region resulting in the variation in the time of bloom. Natural regions in Alberta vary

significantly in the cover area. Combining with the effect of unequally distributed population and human activities, a large proportion of the data are collected from more populated natural regions (Boreal Forest, Foothills and Grassland), which results in a higher accuracy level and completeness in such natural regions. Due to the lack of continued data over time, Canadian Shield is not included in the trend analysis. For the natural regions in which trends are determined, the bloom times in Boreal Forest, Parkland and Grassland are earlier and relatively consistent, while the bloom time in Foothills and Rocky Mountain is significantly later. Elevation and related temperature drops are considered major causes of the late bloom time in Foothills and Rocky Mountain. Rocky Mountain contains the highest elevation among natural regions, which contributes to the coolest summer, shortest growing season, and the coldest winter, which is furtherly reflective of the lowest average temperature over the year. Foothills act as the transition ecosystem between Rocky Mountain and the rest of the natural regions in Alberta, where a descending elevation is observed from southwest to northeast. The altitudinal differentiation in spring phenology is suggested by Vitasse et al. (2009), an altitudinal cline along which populations in low altitudes contain a higher growth rate and earlier growth initiation than the populations at higher altitudes. This differentiation is considered to be contributed by the different extent of selection pressure caused by elevation change. The populations at high altitudes tend to experience a more severe climate and competition, leading to a better tolerance of coldness and a lower growth rate (Korner, 2021).

The geographic variations are also demonstrated in the rate of spring phenology trend. Foothills contains the highest rate of delay in 7 out of 9 studied species from 1987 to 2021, even though the statistical significance of the trend is not evaluated and the trends for Foothills are fragmented due to the discontinuity in data collection, the overall highest delay trend in Foothills

is still considered as a relatively consistent phenomenon. Rocky Mountain is the natural region in which the most advancing trends are observed. Three late-bloom species are observed to advance with a relatively low rate (*Elaeagnus commutate*, *Galium boreale* and *Achillea millefolium*) from 1987 to 2021. This result is also inconsistent with the previous studies, which suggest that the advancing shift in early-flowering species is more influenced by temperature rise than late-flowering species (Fitter & Fitter, 2002; Walther et al., 2002). Prevey et al. (2017) suggested the greater thermal sensitivity of plant phenology in a colder climate. However, according to the findings in this thesis, no particular pattern in the correlation between phenology shift and regional difference in surface temperature is supported, because the highest rate of shifting is not observed in the coldest region (Rocky Mountain and Boreal Forest), and the shift in phenology is considered resulted from the combination of multiple factors than just solely the temperature.

5.3. The limitation in data quality

The data collected in this thesis is wholly based on the Citizen Scientist Network, while the data's reliability and validity are difficult to verify. Due to various factors like lack of experience, expertise or training, the data collected by voluntary observers may contain potential issues which compromise the quality and accuracy of the phenology database generated using citizen science (McDonough et al., 2017). When processing the data, discontinuity in data is one of the major issues which affect the accuracy of the trend analysis. During the data analysis of this thesis, the outliers are not cleared to improve the quality collected by the volunteer observers. Li et al. (2020) analyzed the data collected in Alberta PlantWatch from 1987 to 2016 and suggested five different methods of outlier detection, which should be applied in future research to improve

the data quality. There are two major causes of the discontinuity in data: the discontinuity in the Alberta PlantWatch program itself and the discontinuity in the species occurrence over time.

There is a gap between the current Alberta PlantWatch and its preceding program from 1962 to 1973, while there is completely no systematic record of spring phenology activities during this period. Even though the latter program has provided a database with higher completeness, the decade-long deficient data still leads to biases in the regression analysis. The discontinuity of data is also presented in the same species. For example, Foothills is the natural region in which the most discontinuous trends and outliers are observed. Because of this, the trends of vegetation phenology trends in Foothills is considered somehow biased, while as reflected in the result, the inaccuracy during data collection may be the cause of fragmented and somehow exaggerated phenology trends determined in Foothills.

During the data collection, the environmental condition of the observation is required from observers. However, due to reasons like limited instruction, limited technical support or ignorance of observers, valuable data like weather conditions and geographic conditions are not collected efficiently. Since this thesis has not focused on the factors which affect spring phenology other than warming temperature, the consideration and continuous measurement of related factors is suggested for future study.

6. Conclusion

In this study, we documented a general delaying trend of recent spring phenology in Alberta from 1987 to 2021, which is inconsistent with previous studies, and the expected advance under global warming. However, advance in early-blooming species is observed in the longer-term phenology shift from 1936 to 2021, which is considered reflective of the correlation between

climate change-driven rising temperature and phenology shift. Regional variation is demonstrated in both mid-term and long-term analysis, the rate of shift is significantly higher in colder regions, with Foothills being the region with the highest rate of shift.

Since the phenology research in Alberta is greatly dependent on the citizen scientist network, more observers should be encouraged to join the program to contribute to the database on provincial scale and make the continuing long-term analysis possible.

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